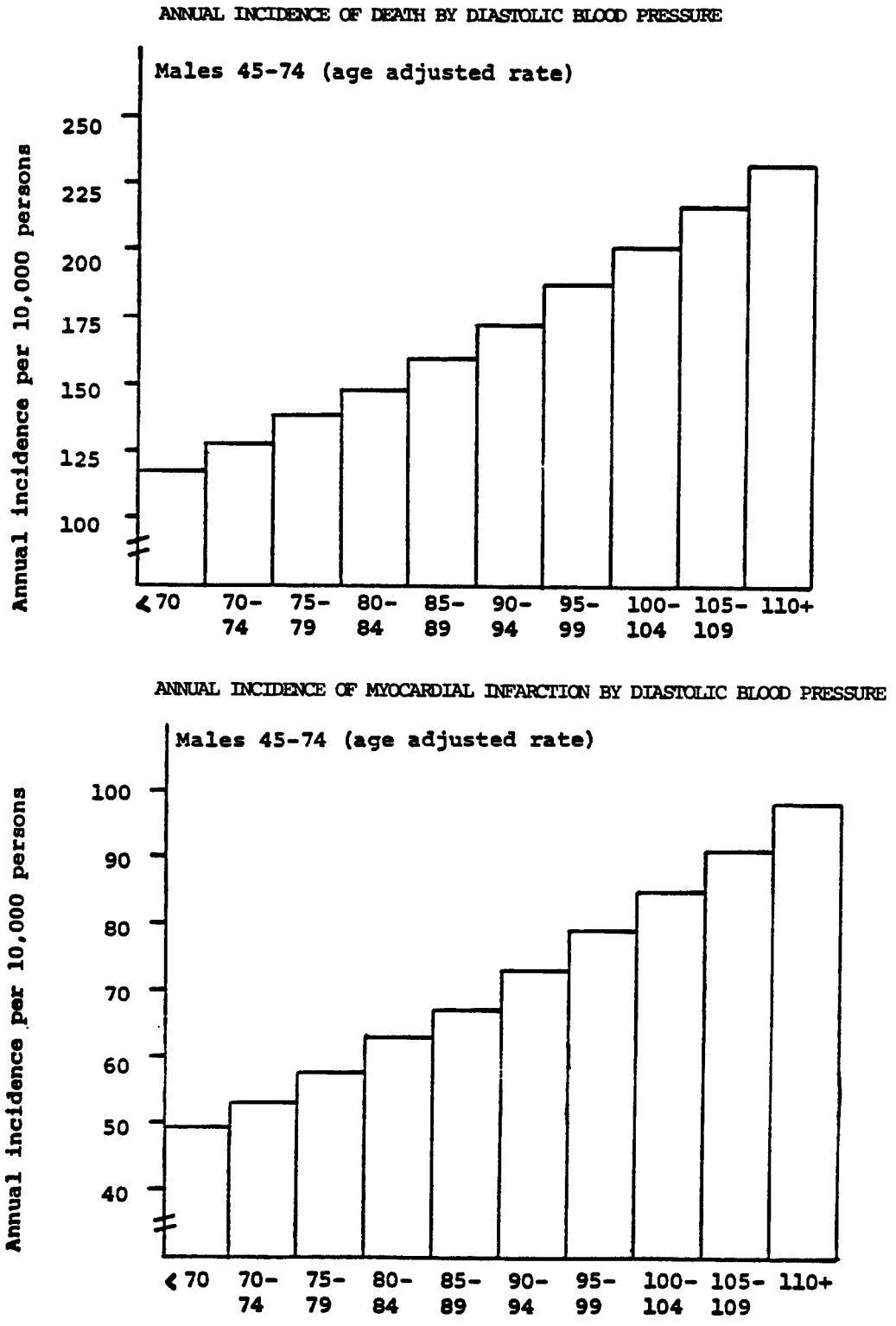
FIGURE IV-1

Adjusted Rates of Death and Heart Attacks versus Blood Pressure: Framingham Data



In addition to estimating the risk of heart attacks, the Framingham study estimated regression equations for the risks of stroke and death as functions of blood pressure and other variables. Because the Pooling Project did not include those endpoints, the Framingham study coefficients are used in this analysis. As with heart attacks, the estimates for strokes cover only first-time events; thus, the estimates for strokes and myocardial infarctions are biased downwards because they exclude second and subsequent heart attacks and strokes associated with elevated blood pressure. The regression equation for deaths covers all CVD-related causes of death; it includes deaths not just from myocardial infarctions and strokes, but also from other causes associated with blood pressure (e.g., heart diseases other than myocardial infarctions).

Levy et al. (1984) recently tested the Framingham study regression coefficients to see how well they explained the observed decrease in cardiovascular mortality in the United States from 1970 to 1980. They found that the coefficients, when coupled with changes in blood pressure and other cardiovascular risk factors over that same period, were able to explain about 80 percent of the drop in cardiovascular mortality.

There is also clinical evidence showing that increased (or decreased) blood pressure can be associated with cardiovascular events and mortality rates. For instance, the Hypertension Detection and Follow-up Program (New England Journal of Medicine, 1982) found that intervention resulting in about a 5 mm Hg change in diastolic blood pressure produced a 20 percent reduction in

overall mortality. The Australian National Trial on mild hypertension also found reductions in morbidity and mortality resulted from lowered blood pressure (Lancet, 1980). The Multiple Risk Factor Intervention Trial found that drug therapy to lower blood pressure reduced cardiovascular disease in persons with normal resting electrocardiograms (ECGs), but increased it in persons with abnormal resting EGGs (Journal of the American Medical Association, 1982). This suggests an adverse effect of the drugs used.

To produce estimates for all 40 to 59 year old white males, the individual risk of each person sampled in the NHANES II was summed and then averaged. Since the sampled individuals represent the U.S. population for their specific age-race-sex category, their average risk represents the average risk for all 40 to 59 year-old white men. Because blood lead levels have dropped since the NHANES II period, we corrected for that change and then evaluated the effects of the potential MCL for lead. Again, only white men were examined because there were too few blacks in the Framingham study, and their risk might be different from whites.

The three cardiovascular-risk regression equations all predict risk over the next 10 years, given current blood pressure, age, and other characteristics. Presumably, the risk in years 2-10 was affected by blood pressure in those years as well as by initial blood pressure. Because blood pressure levels over time in the same individual are positively correlated, it is likely that the regression coefficient in part included the effect of future blood pressure levels. Lacking any data with which to estimate

the pure effect of a one-year change in blood pressure, we divided the coefficient for 10-year risk by 10. The adjusted coefficient was then used with the year-by-year predicted changes in blood pressure to estimate risk reductions. This procedure almost certainly overcompensates, lending a downward bias to the results, because current blood pressure is not perfectly correlated with future blood pressure.

In this analysis, we adjusted the population at risk for the increases in the U.S. population of white males aged 40 to 59. The regression from the Framingham study predicting deaths for men aged 40 to 54 was extended to 40 to 59 for data comparability and uniformity. Because the death rate actually increases with age, this also will bias the results downward.

In this analysis, EPA estimates that there would be 240 fewer myocardial infarctions, 80 fewer strokes, and 240 fewer deaths among the members of the target groups in sample year 1988 as a result of the potential MCL. Extending this analysis to men of other ages and to non-whites would substantially increase these estimates.

IV.B. Lead's Effects upon Reproductive Function

At high levels, lead's adverse effects upon human reproductive function have been known for over 100 years.* In 1860, for instance, Paul published findings that lead-poisoned women were likely to abort or deliver stillborn infants, and articles in the 1880s reported lead to be a teratogen. Because lead passes the

* Indeed, 'lead plasters' were used as abortifacients at the turn of the century.

placental barrier, the most sensitive population for lead exposure may be fetuses and newborn infants, whose source of exposure to lead is, of course, the mother. Lead has been implicated in complications of pregnancy, including early and stillbirths, and possibly low-level congenital anomalies. The effects upon the fetus and neonate are discussed in Section III.C., above. In this section, we summarize some of the reproductive effects upon women and men, but estimates of populations at risk are made only for women. The Criteria Document (1986; p. 12-192 ff) contains a full discussion of lead's adverse effects upon reproductive function. In addition, the Addendum to the Criteria Document (1986; p. A-31 ff) contains a section on growth and developmental effects following pre-natal lead exposure, including some studies of negative pregnancy outcomes.

Because several early studies (many from the 1800s) showed clear adverse effects of lead at high levels upon female reproductive functions, particularly miscarriages and stillbirths, women have been largely -- though not entirely -- excluded from occupational exposure to lead. The mechanisms underlying these effects are unknown at this time. Factors which could contribute range from indirect effects of lead upon maternal nutrition or hormonal state before or during pregnancy to more direct gametotoxic, embryotoxic, fetotoxic, or teratogenic effects that could affect parental fertility or off-spring viability during gestation.

In addition, pregnancy is a stress that may place women at higher risk for lead toxicity, because both iron deficiency and calcium deficiency increase susceptibility to lead, and

women have an increased risk of both deficiencies during pregnancy and post-parturition (Rom 1976). Pregnancy and lactation are also physiological conditions of bone demineralization, when lead as well as calcium and other minerals are released from storage in bones. While this may decrease the total body burden of lead for the pregnant woman, it obviously has potentially toxic consequences for the fetus.

However, there is inadequate information to assess precisely the effects of lead exposure -- at either high or low levels of exposure -- on human ovarian function or other factors affecting female fertility, or on maternal variables, such as hormonal levels, that are known to affect the ability of the pregnant woman to carry the fetus successfully to full term.

While earlier studies focused more upon women, much research is now directed to lead's effect upon male reproductive function.* Lead-related interference with male reproduction function, including gonadal impairment, diminished number and viability of spermatocytes, and apparently exposure-related increases in erectile dysfunction, have been reported. Also, there are several articles implicating exposure of males to lead as the cause of adverse effects on the conceptus (e.g., Singhal and Thomas, 1980). These include low fertility rates, low birth weights, and higher rates for miscarriages and stillbirths in families of occupationally lead-exposed men.

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* As an indication, the chapter on reproductive effects in Singhal and Thomas (1980) discusses males almost exclusively.

IV.B.1. Estimating the Population At-Risk for Female Reproductive Effects

While lead is a fetotoxin and therefore probably dangerous to the unborn even at low levels of exposure, the only data on reproductive effects upon the adult female (as opposed to the fetus)* are at fairly high levels, i.e. > 15 ug/dl. No studies have been conducted on reproductive effects of women with 'normal' lead exposures. Recent studies (discussed in the previous chapter) on the inverse relationship between blood lead levels and gestational age and birth weight and height suggest that reproductive effects of lead exposure observed at high blood-levels continue through the 'normal' range. The available data concerning lead's adverse health effects indicate that the lack of data on reproductive effects at low exposure levels reflects a lack of data and not a finding of no effect.

To assess the adult female population potentially at risk of suffering reproductive effects, we calculated the number of women of child-bearing age (i.e., aged 15-44) above 15 ug/dl who would benefit from this proposed rule. While there is evidence of neurological effects, enzymatic inhibition and metabolic alterations at below 10 ug/dl,** this cut-off was used because at 15 ug/dl, many body systems (e.g., heme synthesis) show indications of significant impairment. This estimate should be understood, therefore, as a

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* Fetal effects related to lead exposure are discussed in Chapter III.

** The Addendum to the Criteria Document (1986) says, "At present, perinatal blood lead levels at least as low as 10 to 15 ug/dl clearly warrant concern for deleterious effects on early postnatal as well as prenatal development." (p. A-48)

low estimate of potential adverse effect. All women of childbearing age and with blood lead levels over 15 ug/dl were considered to be at risk of reproductive effects whether or not they were pregnant, because the damage occurs in any case.

In Section C of Chapter III, estimates are presented of the number of women of childbearing age, i.e. , aged 15 to 44 (24 percent of the total population), and the fraction of them estimated to have blood lead levels over 15 ug/dl in 1988 (0.36 percent). Of the total current U.S. population of a little over 240 million, 219 million people are served by community water supplies, of whom 42 million receive water that exceeds a potential MCL of 20 ug/l . Assuming that women of childbearing age and that women with high blood-lead levels are distributed proportionately throughout the population,*

$$24\% \ \frac{219}{\text{million}} \times 0.36\% \times 42 \text{ million} = 33{,}000$$

women in 1988 will be $\geq$ 15 ug/dl and, therefore, at risk from suffering reproductive effects from exposure to lead. By reducing

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* While it is reasonable to assume that women of child-bearing age are distributed proportionately throughout the population and therefore that they are equally at-risk of receiving water with high lead levels, it is very conservative to assume that women with high levels of lead in their blood are equally distributed in areas with high water-lead levels and low water-lead levels. This is because blood lead levels are one measure of lead exposure; in general, women with high blood-lead levels are exposed to more lead. Because drinking water is one source of exposure, it is more likely that -- all other sources being equal -- women receiving more lead in their drinking water will have higher than average blood-lead levels. While this is logical, there is no empirical data to calculate the increased likelihood. We have used the most conservative assumption: proportional distribution.

the contribution of lead from drinking water, this proposed rule will provide benefits to these women in the form of reduced risk of potential reproductive effects.

Also, as presented in Chapter III, to assess the number of pregnant women at risk of suffering adverse effects as a result of exposure to lead from drinking water that exceeds the proposed MCL, we assumed that pregnant women were distributed proportionately throughout the country and therefore used the national occurrence data to estimate this at-risk population. Of the estimated 54 million women of childbearing age (15-44), about 7 percent are likely to be pregnant at any given time.* Of these, 680,000 are now probably receiving water that exceeds the proposed MCL.

IV.C. Monetized Estimates of Adult Health Benefits: Reduced Cardiovascular Disease Risk in Men

Valuing reductions in morbidity and mortality is a difficult and, to say the least, controversial task. For morbidity, the benefit estimates included avoided medical costs and foregone earnings associated with the diseases. This underestimates social benefits because they fail to account for other important losses associated with disease, including long-term effects, pain and suffering (including, for instance, the paralysis that often follows a stroke). For valuing the reduction in mortality risk, we have chosen a fairly conservative estimate ($1 million per life)

* The rate, according to the Census Bureau, is currently 67.4 pregnancies per 1,000 women of child-bearing age.

from the large range obtained from studies of occupational risk premiums and from other EPA policy papers.

IV.C.1. Hypertension

Whether or not it results in coronary or cerebrovascular disease, high blood pressure is a significant chronic illness. It also generates economic costs, in the form of drugs, physicians' visits, hospitalization, and work loss. Data from the NHANES II and from the National Institutes of Health were used to estimate the value of avoiding a case of high blood pressure.

The NHANES II ascertained how many times per year a person saw a physician because of high blood pressure. The weighted average, for males 40 to 59 years old with diastolic blood report of sure over 90 mm, was 3.27 visits per year. Based upon an average cost of $35 per physician visit, the annual total is $114.

The same population was forced to remain in bed an average of 0.41 days per year because of high blood pressure. At the average daily wage ($80),* that translates to $33 per year. Data from the NHANES II also show that 29 percent of those clinically defined as hypertensive were on medication for hypertension. Using standard medical costs indicating that the average drug cost is $220 per year for those on medication yields an annual cost of $64 (in 1985 dollars).

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* Based upon wage and earnings data in Statistical Abstracts of the U.S. 1985 and the Economic Report of the President 1986.

The National Hospital Discharge Survey (1979) found that, excluding those with heart disease or cerebrovascular disease, people with high blood pressure used 3.5 million of the occupied hospital bed-days that year; dividing by the 60 million people the NHANES II identified as having high blood pressure gives a rate of 0.058 hospital bed-days per person per year. We have assumed that these results apply to the 40 to 59 year old age group of males, as well. Using a daily hospital cost of $450, the annual cost per hypertensive is $26.

Summing these estimates yields a total of $237 per hypertensive per year (1985 dollars). It should be noted that only 29 percent of the people with blood pressure above 90 mm in the NHANES II were on blood pressure medication, in part because some of them had not previously been detected as having high blood pressure. Therefore, the average cost for a detected case will be higher. For example, Weinstein and Stason (1977) used an average cost of $200 in 1975 dollars, or about $486 in 1985 dollars, for treatment of patients undergoing medical care for hypertension. Nevertheless, we have conservatively used $250 as the value of avoiding one case of high blood pressure for one year.

IV.C.2. Myocardial Infarctions

The estimate of the benefits of reducing the incidence of myocardial infarctions relies heavily on Hartunian et al. (1981), who estimated the medical expenses and lost wages associated with a variety of diseases. Under the category of myocardial infarctions (MI), Hartunian et al. examined three types of cases:

sudden death, fatal MI, and nonfatal MI. (Sudden death was classified as a myocardial infarction in the Pooling Project regression coefficients.)

For each category and each age group, Hartunian et al. obtained data on the type of medical services needed (e.g., ambulance or coronary intensive care unit), the fraction of cases using each service, and the costs in 1975 dollars. They also determined the annualized recurrence and follow-up costs, by age, for each condition. These were then discounted (using a 6 percent real discount rate) to the time of initial occurrence to estimate the cost, in current dollars, of each new case. The resulting estimates were $96 for sudden death and $7,075 for both fatal and nonfatal MIs.

These 1975 estimates have been adjusted in three ways to reflect current conditions. First, they are inflated to 1985 dollars. Because most of the costs were hospital-related, with the rest principally being physicians' fees, we inflated the Hartunian et al. cost estimates by a weighted average of 80 percent of the change in the Consumer Price Index (CPI) for hospital rooms and 20 percent of the change in the CPI for physicians' charges.* Approximately 90 percent of the Hartunian et al. MI costs were hospital-related, not physicians' fees, and hospital costs rose faster than physicians' fees, lending a downward bias to the estimates.

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* Using data from Tables B-56 and following, Economic Report of the President 1986.

The second adjustment in the 1975 estimates involves changing cost indices. Because cost indices only account for increased costs of the same procedure, in this case principally the initial hospitalization for a heart attack, they do not reflect the cost of new or different procedures. Since 1975, the fraction of people suffering coronary heart disease who subsequently undergo coronary bypass operations has increased substantially. The number of bypass operations tripled in seven years, from 57,000 in 1975 to 170,000 in 1982, while the number of cases of coronary heart disease has remained relatively constant (National Centers for Health Statistics, Hospital Discharge Survey, and unpublished data) . Based on the Hartunian et al. data, 7.1 percent of MI cases in 1975 had subsequent bypass operations. Assuming that they shared proportionately in the tripling of the bypass operation rate, we estimated that an additional 14 percent of MIs now result in a bypass operation. Hartunian et al. estimated the cost of bypass operations at $6,700 in 1975 dollars, or $18,200 in 1985 dollars. Adding 14 percent of this cost to the other direct costs yields an estimate of the total direct costs in 1985 dollars of $21,700 for an MI and $260 for sudden death.

The third adjustment involved discount rates. Hartunian et al. used a 6 percent real discount rate to present value the future year costs, whereas this analysis employs a 10 percent discount rate. Fortunately, Hartunian et al. performed sensitivity calculations for other discount rates, including 10 percent. Making all of these adjustments, the costs per case are $19,600 for an MI and $233 for sudden death.

Hartunian et al. also obtained data indicating the probability distribution of cases among the different categories. Of the total number of cases in these three categories, about 22.5 percent were sudden deaths and the remaining 77.5 percent were fatal or nonfatal MIs. Applying those percentages to the medical-cost estimates derived above yields a weighted average of $15,230 per myocardial infarction.

Hartunian et al. calculated the present value of foregone earnings based on reduced labor force participation using data on each type of heart disease, broken down by sex and 10-year age categories. Those results are used here, with several modifications. First, foregone earnings for fatal heart attacks are excluded because the reduction in mortality risks is valued separately (see Section IV.C.4. , below). Second, we adjusted for the increase in average non-farm compensation from 1975 to 1985, using information from Data Resources, Incorporated; from the U.S. Census Bureau; and from the Economic Report of the President to Congress. Finally, again a discount rate of 10 percent was used, rather than the 6 percent used by Hartunian et al.

The resulting estimates of foregone earnings are $97,000 for heart attack victims under 45; $51,000 for those between 45 and 54; and $24,000 for those over 55. Based on data from the Pooling Project and NHANES II, 16.1 percent of nonfatal heart attacks in men between 40 and 59 occur in those under 45, 50.9 percent occur in those between 45 and 54, and 33 percent in those 55 and older. Using those percentages yields a weighted average for lost earnings of $49,500 per attack. Combining that earnings

estimate with the earlier one for medical costs yields a total benefit per myocardial infarction avoided of about $65,000 (in 1985 dollars).

IV.C.3. Strokes

The estimates of the benefits of avoiding strokes also rely on Hartunian et al., with similar adjustments. (Unlike myocardial infarctions, the medical cost estimates for strokes were not adjusted to reflect any changes in medical treatment since 1975.) Table IV-1 presents the estimates for three types of stroke -- hemorrhagic, infarctive, and transient ischemic attacks (TIA) -- by age. The averages are based on the distribution of types of strokes and incidence of strokes by age. The overall average is $48,000 per stroke avoided, in 1985 dollars.

We have been unable to estimate a value for avoiding the loss in quality of life that occurs in stroke victims. This is a significant omission. For example, of the people in the NHANES II who reported having had a stroke in the past, 45 percent suffered paralysis in the face and 13 percent still had at least partial facial paralysis, 54 percent suffered paralysis in at least one arm and 21 percent remained paralyzed, 59 percent had numbness in arms or legs and 28 percent had remaining numbness, 30 percent had vision impairment and 13 percent remained visually impaired, and 50 percent had speech impairment with 22 percent continuing to suffer from speech impairment. While there are no estimates of people’s willingness to pay to avoid the risk of these profound injuries, common sense suggests that it is high.

TABLE IV-1. Benefits of Reducing Strokes (1985 dollars per case)

Type of Stroke Age	Medical Expenses	Foregone Earnings	Total
Hemorrhagic			
35-44	$13,600	$44,300	$57,900
44-54	14,300	28,100	42,400
55-64	18,600	11,900	30,500
Infarctive			
35-44	19,000	76,700	95,700
45-54	19,600	46,500	66,100
55-64	25,500	15,100	40,600
Transient ischemic attacks			
35-44	3,450	1,200	4,650
45-54	3,450	3,325	6,775
55-64	3,450	8,950	12,400
Weighted average			$48,000

IV.C.4. Mortality

Valuing reductions in mortality is highly controversial. Over the past decade or so, a substantial literature has developed on the subject. Economists are in general agreement that the best conceptual approach to use is the willingness-to-pay (WTP) of the individuals involved. The appropriate value is not the amount that an individual would pay to avoid certain death, but rather the total sum that a large group of individuals would pay to reduce small risks that sum to one; for example, the amount that 10,000 people would pay to reduce a risk to each of them of one in ten thousand.

Several studies have estimated WTP based on implicit tradeoffs between risk and dollars revealed in market transactions. Most of these studies (e.g., Thaler and Rosen, 1976; Smith, 1974 and 1976; Viscusi, 1978) have studied labor markets, based on the premise that, all else being equal, workers must receive higher wages to accept a higher risk of being injured or killed on the job. Such studies typically regress wages on risk and a variety of other explanatory variables (e.g., levels of education required, worker experience, whether or not the industry is unionized, location, and non-risk working conditions). In such regressions, risk might be measured as the number of fatalities per 1,000 workers per year. The coefficient for that variable is then interpreted as the amount of extra wages needed to compensate for a 0.001 risk of death. Dividing the coefficient by the unit of risk yields the estimate of WTP to avoid a statistical death.

For example, if the coefficient is $500, the estimated WTP is $500,000 (= $500/0.001).

A few studies have estimated WTP in non-occupational settings. Blomquist (1977), for example, estimated the implicit cost-risk tradeoffs that individuals make in deciding whether or not to take the time to put on seat belts.

None of these studies yields definitive answers. All suffer from data limitations (e.g., incomplete information on possible confounding variables and on the extent to which individuals perceive the risks they face). Not surprisingly, given these problems, the studies also yield a wide range of estimates. A recent survey of the literature prepared for EPA found a range of $400,000 to $7 million per statistical life saved (Violette and Chestnut, 1983). Based on that survey, EPA's guidelines (US-EPA, 1984c) do not attempt to set any specific value, but rather recommend that range. To simplify the presentation of the results, this analysis uses a single value from the lower end of that range, $1 million per statistical life saved. Although we do not present any formal sensitivity analyses on this value, the results show that the net benefits are so large that they would remain positive whatever part of that broad range is used; even at $400,000 per statistical life saved, the estimated benefits greatly exceed the costs.

IV.C.5. Summary of Annual Monetized Benefits of Reduced Cardiovascular Disease

Table IV-2 summarizes the annual monetized benefits of reducing the numbers of cases of hypertension, myocardial infarctions,

TABLE IV-2. Summary of Annual Monetized Blood-Pressure Related Benefits of Lowered MCL For Sample Year 1988

Category	Sub-Population Considered	Unit cost (1985 dollars)	Annual Avoided Cases	Total Benefits (millions 1985 dollars)
Cases of hypertension	males, aged 40-59	$250	130,000	$32.5
Myocardial infarctions	white males, aged 40-59	$65,000	240	$15.6
Strokes	white males, aged 40-59	$48,000	80	$3.8
Deaths	white males, aged 40-59	$1 million	240	$240.0
TOTAL (millions 1985 dollars)				$291.9

strokes, and deaths due to high blood pressure that would result from the proposed lowering of the allowable amount of lead in drinking water. These are limited for several reasons:

(1) The hypertension estimate covers only males aged 40 to 59.

(2) The other estimates cover only white males aged 40 to 59.

(3) No value is assigned to reduced pain and suffering associated with hypertension, myocardial infarctions, and strokes,

(4) These are the only adult health effects that are monetized.

Most importantly, these estimates assume a causal link between blood lead levels and blood pressure and assume that reducing body lead burden can reduce blood pressure. In addition, of course, some readers may quarrel with the value assigned to reduced risk of mortality; we have chosen a single value for convenience, not because any particular value can be defended strongly. Despite these limitations, the estimated annual benefits of this potential rule are large, totalling $291.9 million for sample year 1988.

IV.D. Valuing Health Effects: Caveats and Limitations

To begin valuing the health effects that would be avoided as a result of the proposed MCL for lead in drinking water, we have estimated -- for adult males -- the medical costs, lost earnings, and value of lowered mortality risk associated with reducing the number of hypertensives, strokes, and heart attacks (only white males, aged 40-59, were included in the latter two categories). We also estimated the reduction in the number of deaths from all causes (again, only for white males, aged 40-59) resulting from the lowered MCL.

The cost-of-illness estimates themselves are low, primarily because, to reduce potential controversy, the calculations rely on many conservative assumptions. For instance, Hartunian's estimates (used for adult health costs) are based largely upon actual medical practice and not preferred treatment. As a specific example, their panel of medical consultants indicated that only 5 percent of stroke victims would receive anti-coagulant drugs, less than 5 percent would receive any vocational rehabilitation, and that most would receive little or no physical therapy. The real (social) cost of the illness does not decrease if not all victims receive the treatment they need; assuming the treatments are efficacious, stroke victims who are left disabled incur a cost at least equal to the cost of the medication they should have (but did not) receive. The health benefit estimates, therefore, should be understood as very low lower-bounds for these categories of effects.

Cost-of-illness calculations were not conducted for most of the adverse health effects associated with human exposure to lead including the reproductive effects in both males and females discussed qualitatively in Section C. Among the many other effects not valued monetarily in this health benefit analysis are:

- kidney effects, detectable in children at blood lead concentrations of about 10 ug/dl, although the damage is often not manifest until adulthood;
- hematopoietic damage, detectable in children at levels below 10 ug/dl;
- adverse pregnancy and other reproductive effects in women, no threshold indicated;

- nervous system effects in adults, with behavioral functions disturbed at very high levels, a dose-dependent slowing of nerve conduction velocity in occupationally-exposed workers, and peripheral nerve dysfunction at 30-50 ug/dl (central nervous system effects are detectable in children at 10 ug/dl);
- metabolic changes, detectable in children at about 12 ug/dl;
- enzymatic inhibition, with no threshold indicated in adults or children, even below 10 ug/dl;
- all effects on fetuses, although lead crosses the placental barrier and maternal blood-lead values correlate with several adverse outcomes, including fetotoxicity at high levels and brain damage at lower levels;
- cardiovascular effects on older men and black males of all ages, which may be dose-dependent with no threshold;
- genetoxic and carcinogenic effects of lead;
- lead's effects upon the immune system; and
- lead's effects upon other organ systems (e.g., gastro-intestinal) .

Finally, three serious phenomena of lead's adverse effect upon human health were ignored. First, hematopoietic, metabolic, and enzymatic damage have cascading effects throughout the body, which have not been adequately addressed. Second, many of the specific effects have long-lasting sequelae which are not included. And last, there is a significantly greater chance of serious effects later in life, including renal failure and cerebral palsy, even in individuals whose highest detected blood-lead

level was below that associated with the most severe effects and who did not at the time show evidence of lead toxicity; this increased risk also was not included.

In addition to all the categories of adverse health effects for which we have not yet been able to quantify benefits at all, the costs of the illnesses that were calculated greatly underestimate the real (social) benefits of preventing those effects, even for the health categories evaluated. The underestimates occur because some categories of direct costs associated with those effects were excluded, as were all indirect but related costs.

In general, society's willingness-to-pay to avoid a given adverse effect is many times greater than the cost of the illness itself, so cost-of-illness analyses inherently underestimate the benefits of avoiding the adverse effect.* Willingness-to-pay studies indicate that society is usually willing to pay two to ten times the cost of medical treatment, and that in specific circumstances society is willing to pay a hundred or a thousand times the cost of the illness itself in order to prevent its occurrence.

More specifically, in the cost-of-illness analyses, only expenses that are directly related to an individual's medical treatment for the specific symptom being evaluated, at the time the symptom occurs, were included. So, for instance, no costs were ascribed for the possibility of adverse effects from the

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* For instance, in general people would be willing to pay more than the price of two aspirins to avoid having a headache.

medical treatment itself or for the possibility that the specific effect of lead may precipitate or aggravate other health effects (e.g., heart attack and stroke victims are at increased risk of respiratory illness). Related expenses, such as the costs incurred by partially paralyzed stroke victims in purchasing specially designed appliances or retrofitting their existing possessions, or the costs of adapting the home environments for victims of CVD were also excluded. Finally, no value was ascribed to the pain and suffering of those affected; this is an especially significant omission because, as an example, about half of stroke victims are permanently incapacitated or paralyzed.

All the indirect but related costs of lead's adverse effect upon human health were also left out. These include work time lost by friends and relatives of the victims (including spouses); medical research related to the prevention, detection, or treatment of the effects of exposure to lead; the development of new procedures to correct the damage resulting from lead exposure; decreased future earnings for those suffering cognitive damage or physical incapacitation (including behavioral disorders) from lead's adverse effects upon virtually every human system; and the like.

IV.E. Summary of Annual Monetized and Non-Monetized Adult Health Benefits of Reducing Exposure to Lead in Drinking Water

This chapter discussed two major physiological effects resulting from exposure to lead: cardiovascular changes in males aged 40 to 59 and reproductive impairment in women of childbearing age. Of these, only the male cardiovascular effects were monetized.

Estimates of the number of women at-risk of reproductive effects, as well as the number of fetuses potentially at-risk, were presented but no monetary value was ascribed to them. Table IV-3 summarizes the annual monetized and non-monetized benefits of a potential reduction in the MCL for lead for one sample year, 1988.

TABLE IV-3. Summary of Annual Monetized and Non-monetized Health Benefits of Lowered MCL For Sample Year 1988

EFFECT	Sub-Population Considered	Unit cost (1985 dollars)	Annual Cases Avoided	Benefits (millions 1985 dollars)
MONETIZED MALE BLOOD-PRESSURE RELATED EFFECTS				
Cases of hypertension	males, aged 40-59	$250	130,000	$32.5
Myocardial infarctions	white males, aged 40-59	$65,000	240	$15.6
Strokes	white males, aged 40-59	$48,000	80	$3.8
Deaths	white males, aged 40-59	$1 million	240	$240.0
TOTAL				$291.9
NON-MONETIZED FEMALE REPRODUCTIVE EFFECTS				
Adverse reproductive effects	women, aged 15-44 >15 ug/dl	NA	33,000	NA
(pregnancies at risk) (of adverse effects) (- same as at-risk) (fetuses)	pregnant women, aged 15-44	NA	680,000	NA)))

CHAPTER V

BENEFITS FROM REDUCED MATERIALS DAMAGE

This chapter contains a discussion of the materials benefits that will result from reducing the occurrence of lead in drinking water. Lead seldom occurs naturally in source waters;* primarily it is leached from the pipes and solder by corrosive water.** Therefore, reducing the occurrence of lead in public water supplies means reducing the corrosivity of that water.+ Reducing the corrosivity of the water produces materials benefits in the form of decreased corrosion damage, in addition to the decrease in lead. This chapter discusses the characteristics of corrosive water and contains estimates of the potential savings that could accrue to water utilities and to consumers by lessening the corrosivity of their water.

As discussed in Chapter II, the major source of lead contamination of drinking water are the materials of the water distribution

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* Concentrations of lead in ground water in the United States are typically low Lead naturally occurring in surface waters or contributed to water by auto emissions, surface run-off, etc. will generally settle in the sediments before reaching the consumer.

** Corrosion is the deterioration of a substance or its properties due to a reaction with its environment. In this document, the "substance" that deteriorates is the pipe -- whether made of metal, asbestos-cement, cement, or plastic -- and the flux and solder joining the pipes, and the "environment" is water, i.e., we are concerned with internal corrosion. (Pipes and other water treatment equipment can also corrode externally.)

+ An alternative, of course, is to replace all plumbing materials containing lead. This would be extremely expensive, costing probably several hundred billion dollars. (Based upon an estimated average replacement cost of $3,000-$5,000 each for most of the 85 million housing units in the country, and $1,500 for each of the 1-10 million housing units estimated to be likely to have a lead service connection.)

and home plumbing systems. Lead occurs primarily as a corrosion by-product. An analysis of the benefits of reducing lead in public water supplies must, therefore, include the benefits of reducing the source of the contamination, that is, the corrosivity (or aggressiveness) of the water.

While pipes made with lead are often considered the source of lead in drinking water, many studies show that lead solder joints actually contribute considerable amounts, as well. In fact, the data show that newly-installed lead soldered pipes conveying corrosive water may leach much more lead than older lead pipes. In addition, lead may also leach from brass faucets. These issues are also discussed in Chapter II.

The corrosivity of drinking water is important for two main reasons: aggressive water may create or have adverse health effects and the water may cause the plumbing system to deteriorate. Corrosion also affects the aesthetic quality of the water, by staining fixtures, discoloring water (most commonly 'red water'), and causing a bad taste.

Corrosive water can be a health problem* because it leaches contaminants from the supply pipes and distribution system and increases the concentrations of metal compounds in the water. In addition to lead, the metals cadmium, zinc, copper and iron are used in plumbing materials and occur in drinking water as corrosion by-products.

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* The potential relationship between corrosive water and cardiovascular disease is discussed in Chapter IV.

Section V.A. contains a discussion of what makes water corrosive: the characteristics of aggressive water, the chemistry of corrosivity, and corrosion indices. In Section V.B., several analyses of the extent of damage to public drinking water systems from internal corrosion are described, and at the end of the section, these analyses are used to quantify the benefits of reducing the corrosivity of U.S. public drinking supplies.

The Safe Drinking Water Act requires EPA to set limits, Maximum Contaminant Levels MCLs), for drinking water. The National Primary Drinking Water Regulations require that these limits be met at the free-flowing outlet of the ultimate user. Because many metals (including lead) occur in drinking water primarily as corrosion by-products, the degree of corrosivity of a system's water is an important consideration in meeting the MCLS at the tap. However, it is difficult to predict a water's potential corrosivity. In addition, much of the problem of corrosion is associated with home plumbing.* EPA has not established guidelines

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* Utilities are responsible for the integrity of the distribution system and the quality of the water delivered to customers. But there are many factors adversely influencing end-use water over which they have no direct control. These include the age and condition of the mains and service connections (many older cities have lead pipes), the fact that consumers want soft water (because it is easier to make suds), local building codes often required the use of lead solder to join copper pipes in construction (the combination of copper and lead results in galvanic corrosion) , the condition of residential plumbing, the age and condition of the solder throughout the system (lead is leached quickly from newly-applied solder), and generally poor monitoring of end-use water. Finally, most utilities have little control over the financial resources available to correct identified problems: both their spending and rate structures are usually regulated either by the local government or by a public utility commission.

for corrosivity. However, EPA did require utilities to monitor and test for corrosivity characteristics using the Langelier Saturation Index (see Section V.A.4. below), and to identify and report on all materials used within the distribution system by February 1983. The purpose of this one-time event was to identify circumstances where corrosion contamination was likely to occur, and to encourage appropriate corrective action.

The 1986 Amendments to the Safe Drinking Water Act included a provision banning the use of materials containing lead in public water systems and in residences connected to public water systems. While the ban is effective immediately, States have up to two years to enforce the ban.

V.A. The Characteristics of Aggressive Water

Corrosivity is a complex characteristic of water primarily related to pH, alkalinity, dissolved oxygen, total dissolved solids, hardness, velocity, temperature, and other factors. All water is corrosive to some degree. How aggressive a water is depends on its physical and chemical characteristics as well as what substance(s) it comes in contact with -- water that is extremely corrosive to some materials may be less corrosive to others. Usually, corrosion is considered a potential problem only for metals, but non-metallic substances (such as asbestos/cement or cement-lined pipes) can also deteriorate when in contact with water.

Corrosion occurs because of physical and chemical actions between the plumbing materials and the water. The actual

mechanisms of corrosion are usually a complex and interrelated combination of physical, chemical and even biological factors.

V.A.1. Parameters of Water Affecting Corrosivity

The following discussion of the characteristics of water that affect corrosivity summarizes the more detailed presentations in Internal Corrosion of Water Distribution Systems (AWWA-DVGW, 1985), the Corrosion Manual for Internal Corrosion of Water Distribution Systems (EPA, 1984; p. 11-16), and Larson (1975).

PHYSICAL CHARACTERISTICS: The two main physical characteristics that affect corrosion are flow velocity (which can either increase or decrease the corrosion rate depending on other properties of the water) and temperature (generally, the higher the temperature, the greater the corrosion rate).

CHEMICAL CHARACTERISTICS: Most of what is called corrosion is caused by chemical or electrochemical actions. Many of the chemical factors affecting corrosion rates are related, and a change in one may change others.

pH* is a measure of the concentration of hydrogen ion, H^+, in the water, which is important because H^+ is one of the major substances that accepts the electrons given up by a metal when it corrodes. In general, at lower pH levels (< 6.8), most metals will corrode more rapidly than at higher pH levels (> 9.0). However, under certain conditions corrosion can occur at high pH.

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* This definition is based upon the discussions in Schock and Gardels, 1983 and US-EPA, 1984.

Corrosion can also occur throughout the range of 5-9 if no protective film is present. pH may not have a strictly linear relationship to lead levels in water. The pH level also affects the formation or volubility of protective films on the inside of a pipe.

Alkalinity is a measure of a water's ability to neutralize acids. In potable water, alkalinity is mostly composed of carbonates, which can neutralize acids, and bicarbonates, which can neutralize bases as well as acids. This property is called "buffering," and can best be understood as resistance to change in pH. Alkalinity affects a water's ability to form a protective coating of lead or calcium carbonate which is especially important in reducing the dissolution of lead. Water with low alkalinity (i.e., under 60 mg/l as $CaCO_3$)·or or very high alkalinity (> 150 mg/l) is generally corrosive.

Hardness is caused predominantly by the presence of calcium and magnesium ions and is expressed as the equivalent quantity of calcium carbonate ($CaCO_3$) in the water. Hard waters are generally less corrosive than soft waters if sufficient calcium ions and alkalinity are present to form a protective calcium carbonate lining on the pipe walls. (A thin layer of $CaCO_3$ is desirable, as it keeps the water from direct contact with the pipe and reduces the chance of corrosion. "Scaling" occurs when thick layers of $CaCO_3$ are deposited. Although the pipe is then protected from corrosion, excessive scaling can reduce the carrying capacity of the system, reduce the efficiency of water heaters, clog water meters, etc.)

Dissolved oxygen (DO) is another substance that accepts the electrons given up by the corroding metal and so allows the corrosion reactions to continue. Oxygen also reacts with hydrogen released by the cathode (see the following discussion on the electrochemistry of corrosion) and with any ferrous iron ions. Occasionally, oxygen may react with the metal surface to form a protective coating of the metal oxide.

Chlorine lowers the pH of the water, making it potentially more corrosive. In addition, because chlorine is a strong oxidant, it can increase a water's potential corrosivity. A few studies have also shown a difference in corrosion rates depending upon whether the water is chlorinated or chloraminated.

Chlorides and sulfates may cause metal pipes to pit by reacting with the metals and creating soluble metal ions, thus preventing the formation of protective metallic oxide films. Chloride is about three times more active in this than sulfate. Higher total dissolved solids (TDS) indicate a high ion concentration in the water, increasing conductivity, which in turn increases the water's ability to complete the electrochemical circuit and to conduct a corrosive current.

Other factors include the presence of hydrogen sulfide (generally accelerates corrosion), silicates and phosphates (both of which can form protective films), and natural color and organic matter (which can either inhibit or encourage corrosion, depending upon other characteristics).

BIOLOGICAL CHARACTERISTICS: Both aerobic and anaerobic bacteria can induce corrosion locally, and many organisms form precipitates with iron.

V.A.2. The Electrochemistry of Corrosivity

Generally, metals are most stable in their natural form, i.e., the form in which they occur in native ores and from which they are extracted in processing. The tendency of a metal to return to its natural state (called activity) is the primary cause of corrosion. Some metals are more active than others and more easily enter into solution as ions or form various compounds. Zinc, iron and lead are more active than, for example, copper or stainless steel.

The process by which metals corrode in water is electrochemical: when a metal enters a solution as an ion or reacts in water with another element to form a compound, electrons will flow from certain areas on the metal's surface to other areas through the metal. An anode is that part of the metal surface that is corroded and from which electric current flows through the metal to the other electrode. The cathode is the metal surface from which current leaves the metal and returns to the anode through the solution. This completes the circuit. All water solutions will conduct a current, a property measured by "conductivity." The anode and cathode areas may be right next to each other or in different areas of the pipe, and they can set up a current in the same metal or between two different but connected metals.

V.A.3. Types of Corrosion

There are many types of corrosion, which can be either uniform or non-uniform. Uniform corrosion results in an equal amount of material being lost over an entire pipe surface; except in extreme cases, the loss is often so minor that the service life of the pipe is not adversely effected. On the other hand, non-uniform corrosion attacks smaller, localized areas of the pipe, causing holes, restricted flow, or structural failures. Non-uniform corrosion is a serious problem.

There are five basic types of corrosion. Galvanic corrosion occurs when two different metals or alloys come in contact with each other or are in the same environment (e.g. , water). This usually occurs at plumbing joints and connections. Due to the differences in their activity, the more active metal corrodes. Galvanic corrosion is common in household plumbing where different types of metals are used, for instance, copper pipes are joined to galvanized iron pipe or copper pipes are joined together by lead/tin solder.

Pitting is a damaging, localized, non-uniform corrosion that forms pits or holes in the pipe surface. It actually takes very little metal loss to cause a hole in a pipe wall, and failure can be rapid. Pitting is frequently caused by ions of a more-active metal plating out on the pipe surface.

Tuberculation occurs when pitting corrosion products build up at the anode next to the pit.

Erosion corrosion (or abrasion) mechanically removes protective films, such as metal oxides and $CaCO_3$, which serve as

protective barriers against corrosive attacks. Generally, it results from high flow velocities, turbulence, changes in flow direction, and/or the abrasive action of suspended materials.

Biological corrosion results from a reaction between the pipe material and the by-products of organisms such as bacteria.

Dealloying or selective leaching is the preferential removal of one or more metals from an alloy in a corrosive medium.

V.A.4. Corrosion Indices

Several indices have been developed to estimate the corrosion potential of specific waters, but because they generally measure the tendency of a specific water to form a protective coating of calcium carbonate, none of these has been entirely successful in predicting whether or not a water is actually corrosive (Larson, 1975; Hoyt et al., 1979; AWWA-DVGW, 1985; etc). The three most commonly used indices (the Langelier Saturation Index, the Aggressive Index, and the Ryznar Stability Index) consider calcium, alkalinity, and pH as parameters to determine the corrosive tendency of the water. However, corrosivity is a complicated and interrelated function of these three characteristics and many others, and each parameter may independently affect the corrosive tendencies of the water. Consequently, some water may be very corrosive even though the measured indexes indicate relatively non-corrosive conditions, or vice versa. It is generally agreed that these indexes are applicable only within a limited pH range, are dependent upon the presence of calcium and alkalinity, and are most appropriate for the materials for which the index was

developed; they are weakest with waters of relatively low alkalinity and calcium.

The Langelier Saturation Index (LSI) or Langelier Index (LI), developed in 1936, is one of the first and most widely used: it expresses the potential of the water to either dissolve or precipitate calcium carbonate. The LSI is defined as the difference between the measured pH of the water and the pH at which $CaCO_3$ would be at saturation concentration. The saturation value of the water with respect to $CaCO_3$ depends on its pH, calcium ion concentration, alkalinity, temperature, and total dissolved solids, such as chlorides and sulfates; but the LSI focuses particularly on the effect of pH upon the volubility of $CaCO_3$. A positive LSI value indicates over-saturation and a negative value indicates an undersaturation of $CaCO_3$; a value of zero indicates equilibrium. In other words, a positive LSI indicates a tendency for the water to deposit a protective $CaCO_3$ layer on the pipe, and hence impede corrosion. Negative values indicate a water's tendency to dissolve $CaCO_3$ from the pipe's interior and, thus, a tendency to be aggressive to the pipe. The index is directional only, not quantitative.

The Aggressive Index (AI) is a simplified version of the LSI developed specifically for asbestos pipes. It assumes typical values for total dissolved solids and for temperature. The AI is nearly interchangeable with the LSI for most practical purposes.

Another common measure is the Ryznar Stability Index (RSI), which uses the same parameters as the LSI. Other corrosion indices include the Larson, (McCauley) Driving Force, and the Riddick Corrosion Index.

V. A.5. Plumbosolvency and Other Factors Determining Lead Levels in Drinking Water

Chapter II contains a more detailed discussion of the potential contamination of drinking water by lead, the sources of that contamination, and potential human exposure resulting from it. This section briefly summarizes the major factors responsible for the contamination of drinking water by lead.

The lead used in service pipes or as part of lead/tin solder is designed to be structurally relatively resistant to corrosion. In addition, the corrosion rate can be decreased by a relatively insoluble coating that forms on the surface of the metal. However, the combination of copper piping with tin/lead solder found in most residences produces galvanic corrosion that can yield lead levels one to two orders-of-magnitude higher than expected from the composition of the water alone. Many studies found that lead solder, especially newly-applied solder, used with copper household pipes was sufficient to raise lead levels above the current MCL, even with relatively non-corrosive waters.

With lead solder, the age of the solder is the single most important variable affecting volubility. As an example, Sharrett et al. (1982a), studying Seattle -- a city with few lead pipes -- found that the age of the house (a proxy measure for the age of the plumbing materials, including solder) was the dominant factor for predicting the concentration of lead in the tap water. In homes that were newer than five years old, with copper pipes, the median lead concentration for standing water was 31 ug/l versus 4.4 ug/l in older homes. The median lead level was 74 ug/l in

homes built within the previous 18 months. New solder will leach lead even in relatively non-corrosive water -- whether naturally exhibiting low corrosivity or treated -- and it can continue to leach significant amounts for up to five years.

Two other factors will affect the rate of lead leaching from lead-soldered joints: the surface area of the lead/tin solder at the joints and the number of joints per length of pipe.

The duration of contact need not be long. Britton and Richards (1981) have shown that, with corrosive water, lead levels in systems with copper plumbing joined with lead solder could rise above 100 ug/l within 40 minutes of contact. Oliphant (1983) has presented evidence that these conditions can produce lead levels one to two orders-of-magnitude higher than expected from equilibrium volubility calculations.

Several characteristics of <u>lead piping</u> mentioned in decreasing order of significance, also influence lead levels in drinking water. The length of the lead pipe, in both the home and the supply lines, can have a positive association with lead levels as can the position of the lead pipe. The ratio of the surface area of lead exposed to the water volume contained is another important variable. The age of the dwelling and the percentage of lead piping in both the service mains and within the residence were also relevant factors in determining lead levels. The number of occupants of the dwelling is inversely proportional to lead levels, probably because fewer occupants mean the water will, on average, remain in the pipes longer (Department of the Environment 1977; Pocock, 1980).

Lead can also leach from copper pipes themselves (Herrera et al., 1981). Specifications for copper pipes usually limit only copper and phosphorus, and copper used for non-drinking water applications is permitted to contain some lead. Copper pipe manufacturers have indicated that copper tubing for water is made from the recycled copper products which could result in the introduction of lead impurities (Herrera et al., 1981). Although not common, lead impurities can also occur in galvanized pipes and from stabilizers used in plastic pipes.

Lead is also used in the production of brass and bronze. Brass is a copper-zinc alloy, which can contain up to 12 percent lead, and bronze is a copper-tin alloy, which can contain up to 15 percent lead (U.S. EPA, 1982b). Both are relatively corrosion resistant, although several studies document lead leaching from bronze and brass fixtures. Additional analysis of the leaching of lead from these and other materials is needed.

With even mildly aggressive water, any amount of lead anywhere in the distribution system or household will contribute lead to the drinking water. Overall, the degree of corrosivity, the length of time in the pipe, the total amount of lead in the plumbing system and the newness of the plumbing are the chief determinants of lead concentrations.

In general, with relatively corrosive waters, lead levels in 'first draw' water can be several times higher than in 'running' samples. With aggressive waters and new solder, however, first-draw samples can be an order-of-magnitude or more greater.

V.B. Damage to Public Water Systems from Internal Corrosion

Because lead contamination of drinking water occurs most often as a result of the corrosive action of water upon the materials of the public and private plumbing systems, strategies to mitigate this contamination will have to include corrosion control efforts. Corrosion in water supply distribution systems has economic impacts as well as potentially creating health hazards. It also can affect the aesthetic quality of the water. The corrosion rate within a specific water system is a function of the character of the water, the materials used in the distribution system, and of flow conditions. But notwithstanding the local differences, corrosion is a universal problem: corrosion occurs with all metals currently used in plumbing equipment and construction, and also with asbestos-cement and cement pipes. Corrosion impartially destroys the distribution system mains, service lines and private household plumbing; reduces the flow capacity and increases operating costs throughout the distribution system; and causes water loss through leaks and pipe breaks.

Corrosion control treatment will produce substantial benefits in the form of reduced damage to public and private plumbing systems, as well as reducing exposure to lead which will produce the health benefits described in Chapters III and IV.

V.B.1. Occurrence of Corrosive Water in the United States

Data on the extent of aggressive water in the United States are incomplete. The most commonly held profile of the corrosivity of U.S. drinking water relies on data on 600 public supply systems

collected in 1962 by the U.S. Geological Survey (Durfor and Becker, 1964a). That study identified the Northeast, Southeast and Northwest parts of the country as having relatively soft and aggressive waters.* Of the 26 states in those regions, 17 had very soft water (under 60 mg/l as $CaCO_3$): Alabama, Connecticut Delaware, Georgia, Maine, Maryland, Massachusetts, Mississippi, New Hampshire, New York, North Carolina, Oregon, Rhode Island, South Carolina, Vermont, Virginia, and Washington. In 1980, these states had a combined population of 67.7 million people. Figure V-1 presents the USGS state findings.

Also during the early 1960s, the U.S. Geological Survey conducted a survey of the aggressiveness of public water supplies in the 100 largest cities in the country (Durfor and Becker, 1964b). The profile of water corrosivity in this study correlated fairly well with the state study: the Northeast, Southeast, and Northwest are most at risk of very soft water.

In 1974 and 1975, the National Center for Health Statistics (NCHS) conducted an extensive health examination survey of 4,200 randomly selected individuals representing 3,834 households in 35 geographic areas across the country. This was called the National Health and Nutrition Examination Survey, augmentation survey, or HANES I, augmentation survey. For each geographic area, the Bureau of Census selected 120 individuals to provide a "representative" sample of the U.S. population. EPA participated in this

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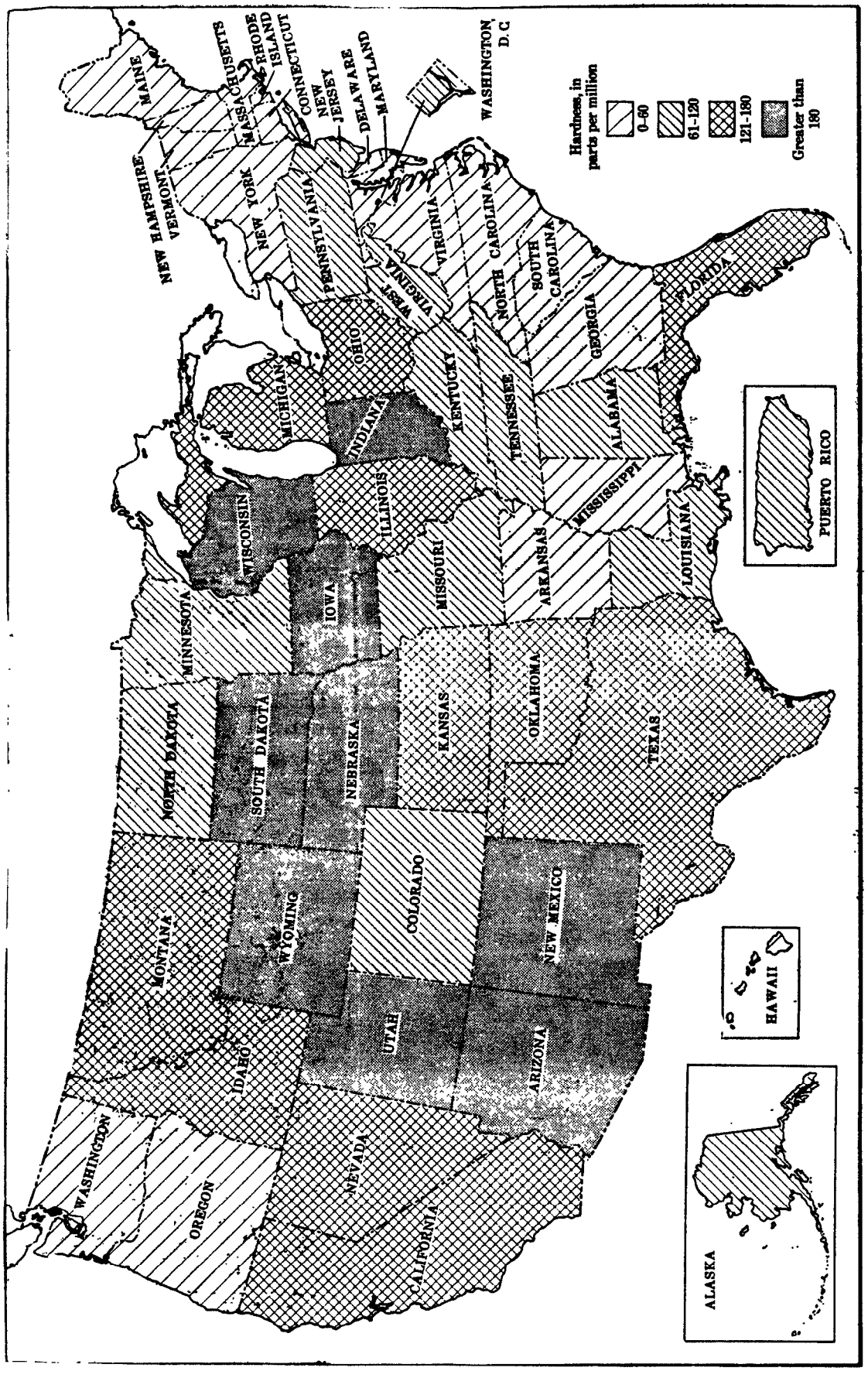
* While these studies present "average" data on water by state, it should be noted that water (parameters and quality) varies significantly within states, as well.

FIGURE V-1. 1962 U.S. Geological Survey of Water



MAP F.— *Hardness of finished public water supplies of the United States and Puerto Rico, 1962.*
(Average weighted by population served)

SOURCE: Durfor and Becker, Chemical Quality of Public Water Supplies of the United States and Puerto Rico, 1962. U.S. Geological Survey, 1964

survey to assess the role of drinking water quality and cardio-vascular disease. As part of this survey, the NCHS collected a 1-quart "grab" sample of water from the kitchen faucet of each participant, which was sent to EPA for analysis.

Several studies have presented the data from this survey; unfortunately, the results differ from study to study, and the entire data set is currently being re-analyzed at the University of Pittsburgh. One study (Greathouse and Osborne 1980) indicates that about one-third of the U.S. population is exposed to very soft water (i.e. , under 60 mg/l as $CaCO_3$) and that the median U.S. drinking water is about 91 mg/l-$CaCO_3$. Another paper (Greathouse and Craun, 1978) presents mean concentrations at 119 mg/l. A third study, Millette et al. (1979), presented the following distribution of aggressive water provided by utilities (using the Aggressive Index as a measurement):

16.5% of utilities had highly aggressive water (i.e., AI $\leq$ 10.0),

52% of utilities had moderately aggressive water (i.e., AI = 10.0-11.9),

31.5% of utilities had non-aggressive water (i.e., AI $\geq$ 12.0).

No results were presented by Millette on the distribution of population served by those utilities. However, if the average water system serves 3,650 people, this distribution suggests that 36 million people are exposed to very aggressive water and another 114 million people are exposed to moderately aggressive water.

Hudson and Gilcreas (1976), basing their analysis upon the U.S. Geological Survey data, estimated that half of the water

distributed in the U.S. is naturally corrosive, and is either untreated or, for whatever reason(s), the treatments are not achieving chemical stability. While the specific data they evaluate are related to the 100 largest cities (Durfor and Becker, 1964b), they assumed that larger systems generally provide better water than smaller systems. Hudson and Gilcreas then extrapolated linearly to the rest of the country.

In 1979, the A/C Pipe Producers Association commissioned the Midwest Research Institute (MRI) to survey the occurrence, economic implications and health effects associated with aggressive waters in public water supply systems. MRI surveyed more than three-quarters of the largest (i.e., serving over 50,000 people) public drinking water systems in the country and about 10 percent of the medium-size (serving 10,000-50,000) systems. Their results (using the Langelier Saturation Index) are extremely close to those of Millette et al.:*

16% of utilities surveyed had highly aggressive waters (i.e., LSI < -2.0),-

51.5% of utilities surveyed had moderately aggressive waters (i.e., -2.0 < LSI < 0.0),

32.5% of utilities surveyed had non-aggressive waters (i.e., LSI > 0.0).

They estimated the population exposed only for the utilities they sampled; they did not extrapolate to the rest of the country, or attempt to draw a national profile from their data. However, over 171.1 million people are served by medium and large systems.

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* The MRI categories using the LSI correspond directly to Millette et al.'s, who used the AI.

Also in 1979, Energy and Environmental Analysis (EEA), using internal data from 1970, estimated that about 27 percent of the U.S. population or 55 million people in 1970 were exposed to very soft water. This includes most of the population in the northeastern, southeastern and western states. While EEA did not cite the source of their data, their map of soft water areas is very similar to the 1962 U.S. Geological Survey.

In Patterson's 1981 analysis using 1978 data from Culligan dealerships throughout the country,* 7 states (Alabama, Connecticut, Mississippi, North Carolina, Oregon, Rhode Island, and South Carolina) had soft water, i.e., under 60 mg/l as $CaCO_3$, with a combined population in these states of 22.1 million people (1980 Census). This is a low estimate of soft water occurrence because the data come from a company providing water-softening services and represent people with harder-than-average water; indeed, the average water hardness in the Culligan data is significantly higher than other data.** Notwithstanding this bias in the data, the profile of the country presented by these data support the U.S. Geological Survey map of hard and soft water areas in the country.

V.B.2. Corrosion Damage

Corrosion can take place at the treatment plant, throughout the distribution system, and in household plumbing, and it has many effects that cost utilities and consumers money. Corrosion results in pipes breaking, damage to meters and storage facilities,

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* This data set is described in Chapter II. The use of company names and the presentation of related data does not constitute endorsement of these services.

** This issue is discussed in Section II.B.1 , above.

water loss, excess repair and replacement of equipment water damage from leaks, increased pumping costs due to the reduced hydraulic efficiency of corroded or partially blocked pipes, loss of service pressure, and increased operating costs associated with all of these effects. In addition, consumers suffer damage to private hot water heaters, radiators and faucets. Corrosion products also retard heat transfer for heating or cooling water, increasing both water use and operating costs.

EPA has determined (1977) that, as an upper limit, as much as half the water leaving a treatment plant may be lost before ever reaching the consumer. More conservatively, the National Science Foundation has estimated that, nationally, 15 percent of the water distributed is lost. Of course, not all of this Loss results from corrosive water; some is due to accidents or other naturally occurring events. MRI (1979) calculated that 38 percent of all water loss or 6 percent of total water distribution is lost due to corrosion from aggressive waters.

MRI's survey of public water utilities indicated that corrosion-related repairs in utilities with non-aggressive water were about 62 percent of those in utilities distributing relatively aggressive water. Data from other studies show that reducing the corrosivity of the water could -reduce corrosion damage rates by at least 20 percent (Bennett et al., 1979, cited in Ryder, 1980) or even 30-75 percent (Dangel, 1975; Kennedy Engineers, 1978). These surveys also show that pipe and equipment replacement and repair due to scaling, leakage or breakage* is the major economic

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Delaying the first break is important because while the probability of a break increases with age, once a break has occurred, the probability of another one is many times higher.

effect of corrosion in distribution systems and that within this category, pipe replacement is the primary maintenance item.

Studies that present monetary estimates of corrosion damage have generally focused upon either the cost to the utility or the cost to the private residence owner; few have done both. Those studies that have tried to include all the costs of corrosion damage have, by and large, covered smaller geographic areas -- a city or metropolitan area, typically.

V.B.3. Estimating the Annual Costs of Corrosive Water

Projections of the economic impact of corrosive water evidence a wide range of factors of concern, assumptions and methodologies, producing, of course, a wide range of "costs." However, including all of the components of the problem and converting costs to comparable-year estimates the assumptions and methodologies in the different studies produce a much narrower range of cost estimates than seems likely from an initial review of the literature.* The factors that must be considered in calculating the annual benefits of reducing corrosivity include the percentage of corrosion damage that is avoidable by water treatment, the relative damage to public and private plumbing systems, total annual estimates of corrosion damage, and the occurrence of corrosive water in the U.S. For comparability, we have calculated per capita estimates and converted all costs to 1985 dollars using fixed-weighted price indexes from the 1986 Economic Report of the President.

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* This is all the more surprising because each of the "averages" (costs, damages, water characteristics, etc.) is the mean of a distribution of rather large-range values.

All water is corrosive to some degree. Estimates of the incremental damage from particularly corrosive water and, hence, the potential benefits of corrosivity control treatment vary. Several studies of the highly aggressive water in Seattle, Washington (both pre-treatment: e.g., Kennedy Engineers, 1973 and 1978; Dangel, 1975; and post-treatment, e.g., Courchene and Hoyt, 1985) suggest that water treatment could reduce corrosivity damage by 30-75 percent,* or even more (AWWA-DVGW, 1985).

Hudson and Gilcreas (1976) assumed that corrosive water doubles natural deterioration rates, and Kennedy Engineers (1978) used a 50 percent point estimate of avoidable damage from corrosion. EEA (1979) and MRI (1979) took a conservatively low point-estimate (38 percent) from the range presented in the earlier Seattle studies; similarly, Kirmeyer and Logsdon (1983) posit that treatment can reduce corrosivity by 40 percent. Even more conservatively, Ryder (1980) projected that savings from corrosion control would be 25 percent of the total, and Bennett et al. (1979, cited in Ryder, 1980) estimated that 20 percent of water supply corrosion costs were avoidable.

Estimates of the proportion of total corrosion damage (maintenance and capital expenses) borne by the private sector**

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* Kennedy Engineers suggests that although corrosion damage can be reduced by 30-75 percent, costs can only be reduced by 15-50 percent. This distinction is also made in Internal Corrosion of Water Distribution Systems. (AWWA-DVGW, 1985).

** Of course, costs incurred by utilities are eventually passed on to consumers. However, by private sector costs we mean those incurred directly by owners of buildings, and not by the utility.

(primarily homeowners, but also building owners) range from "fully half" (EPA, 1977) to 95 percent (e.g., Dangel, 1975; Ryder, 1980).* Consumer costs are probably higher than distribution costs for several reasons.

- Residential piping is often composed of copper or galvanized steel piping joined by brass fittings or lead/tin solder; combinations of dissimilar metals are particularly vulnerable to galvanic corrosion.
- Water used in the home is often heated, increasing its corrosive potential.
- The materials used in residential plumbing are often less resistant to corrosion and less well-protected than the materials used in distribution systems (AWWA Committee Report, 1984).
- Piping in residences is typically smaller than service mains and flow rates are more variable (both higher and lower), exacerbating many physical characteristics affecting corrosion rates.

Three studies set out to calculate only the costs borne by the water utility. Bennett et al. (1979, cited in Ryder, 1980) used 1975 data from the National Bureau of Standards, which estimated that annual corrosion costs to the overall U.S. economy were $70 billion, of which annual water supply corrosion costs for

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* In general, the highest estimates of the proportion of damage borne by the private sector are based upon data from Seattle -- a city with a relatively new and corrosion-resistant distribution system. Older cities with less well-protected systems can incur a higher proportion of the total damage, and the total costs will be higher.

distribution systems were $700 million ($1,693.9 million in 1985 dollars). That study assumed that 20 percent of corrosion damage is avoidable through water treatment and estimated the annual benefits to utilities of reducing corrosivity at $1.88 per capita in 1985 dollars. Hudson and Gilcreas (1976) estimated annual savings of $375 million ($782.3 million in 1985 dollars) to community and other public water supplies from treatment to reduce corrosivity; their estimate assumed that aggressive water doubles the natural deterioration rate, decreasing distribution capacity by 2 percent annually, instead of one percent. The per capita annual estimate calculated from this study is $4.34 in 1985 dollars, but it does not include all increased operating costs from corrosion damage. The third study of utilities, Kennedy Engineers, 1973 (cited in Anderson and Berry, 1981), estimated the annual per capita damage from Seattle's highly corrosive water at $2.21 ($5.57 in 1985 dollars). Assuming that 30 percent of those damages were avoidable costs, this yields annual benefits of $1.67 per capita for avoided damage to utility systems.

If utility costs are half of private costs,* these three annual per capita estimates of avoidable damage to utilities (in increasing order, $1.67, $1.88 and $4.34, in 1985 dollars) would yield total annual per capita benefits of $5.01, $5.64 and $13.02 (1985 dollars) for reducing corrosivity.

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* That is,

1) total costs of corrosion damage = cost to utilities and cost to private sector,
and cost to utilities = 1/2 cost to private sector,

2) benefits of corrosion control = avoidable damage (% decrease in damage) x total costs of corrosion.

Two studies (Kennedy Engineers, 1978; and Kirmeyer and Logsdon, 1983) calculated the savings that would accrue to private residence owners from treatment for aggressive water. Kennedy Engineers, studying Seattle, estimated that the cost of corrosivity damage could be reduced by 20 percent, and calculated that owners would save $7.50 per year per residential unit ($13.57 in 1985 dollars) if Seattle's highly aggressive water was treated. Using demographic data in the article, this yields annual per capita benefits of $6.17. Kirmeyer and Logsdon, using a 'typical' situation, assumed that corrosivity control could reduce damage by 40 percent, yielding present value benefits of $244 per unit ($292.59 in 1985 dollars) over the remaining life of the plumbing. Using data from the article and the AWWA, this yields annual per capita benefits of $9.44 (1985 dollars). If private costs are two-thirds of total costs (i.e., double the costs -- or benefits -- to utilities), these two per capita annual estimates of benefits to residential owners ($6.17 and $9.44, in 1985 dollars) would yield total avoidable corrosion damage benefits of $9.26 and $14.16 per capita per year, in 1985 dollars.

Finally, two other studies, Energy and Environmental Analysis (1979) and Ryder (1980), estimated total savings from treating water to reduce its corrosion potential. EEA, using data from Dangel (1975) and Kennedy Engineers (1973), considered pipe damage to both the public and private sectors and calculated potential annual savings of $2.67 per capita ($4.54 in 1985 dollars). This

is an admitted underestimate because they did not include total increased operating costs (to either the public or private sector), damage to residential hot water heaters or utility equipment other than pipes, etc., and they assumed that residential damage rates are equal to utility rates; their assumed corrosion rate is also lower than other studies. Ryder, using data collected while he was associated with Kennedy Engineers, calculated total annual corrosion damage in Seattle at $7.4 million ($11.7 million in 1985 dollars), * of which 25 percent could be avoided by water treatment; this yields potential benefits of $5.84 per person per year (1985 dollars) from control of Seattle's highly corrosive water.

For comparison, Mullen and Ritter (1980) published results on efforts by the Middlesex Water Company in Woodbridge, New Jersey, to reduce damage to their unlined cast iron water mains from their soft and aggressive water. Those treatment efforts were rewarded by reductions in corrosion rates of 70-80 percent, averaged over a 5-6 year period. Alternatively, Hahin (1978) assessed corrosion damage as a function of total operating expenses. His analysis of four Air Force and three Army bases showed that corrosion costs averaged 8-25 percent of total annual operating costs over a 10-year period.

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* This is also somewhat of an underestimate (and Ryder presented it as such) because it does not include costs to the suburban water agencies who buy and use Seattle's water, the costs of deterioration of copper pipe, or the costs associated with water conditioning or treatment to minimize corrosion in industrial and institutional buildings. Ryder estimates that the total cost probably exceeds $10 million ($15.8 million in 1985 dollars). Because our costs are all per capita, we would then have to divide this larger figure by the population of the entire metropolitan area.

We have not used cost estimates from two studies: MRI (1979) and Anderson and Berry (1981). In the MRI study, the self-reported expenditures attributable to corrosion totalled $8.3 million annually for the utilities surveyed. (Note that this is not a national estimate and that it is an estimate of expenditures, not damage.) The largest estimate in that survey was much higher than any of the others, indicating either more serious problems for that utility or that they misinterpreted the question. Eliminating that utility drops the estimated costs to $3 million annually for the surveyed utilities. The corresponding per capita costs are $1.15 (including all the utilities) or $0.42 (omitting the outlier); converting to 1985 dollars yields $1.96 and $0.71, respectively. However, the question asked in the survey, "What are your annual costs due to corrosion?", could easily lead to an underestimate of real costs, for several reasons. First, the utilities reported only on their expenditures and not on those incurred by consumers (which could be much greater). Second, the utilities reported only on their expenditures and expenditures are a poor estimate of damage; the utilities did not quantify the damage that was occurring (for example, leaking but not broken pipes) but for which they were not (yet) paying (specifically identified) money. Finally, it is unclear from the data whether any of the utilities identified increased operating costs associated with corrosive water (for example, water loss from leaks or the increased energy costs of pumping water through pipes partially clogged with corrosion by-products) or the proportion of regular maintenance costs (e.g. leaks and breaks) that are attributable to corrosion damage. From the

information presented, it is likely that only major capital expenditures were included.

Anderson and Berry (1981) evaluated the costs and benefits of regulating corrosive water. They used the arithmetic mean ($2.37 per capita) of the EEA and Hudson and Gilcreas studies cited above, $2.67 and $2.08 per capita respectively, as their estimate of the materials benefits of reducing the corrosivity of drinking water. However, none of the monetized estimates in the Anderson and Berry article were first converted to same-year dollars, so they are not comparable. Furthermore, the EEA estimate includes both private and distribution costs while the Hudson and Gilcreas analysis considers only distribution costs; again, the estimates are not comparable. Finally, Anderson and Berry didn't estimate an independent measure of benefit, but relied upon previous work. Because we have included the material they cite, their analysis offered no independent and additional data.

The range of estimated benefits from treatment to reduce the corrosivity of water is, then, from $4.54 (the admitted under-estimate in EEA, 1979) to $14.16 (Kirmeyer and Logsdon, 1983), both in 1985 dollars, per person per year. Table V-1 summarizes all the studies.

V.B.4. Monetized Benefits of Reduced Corrosion Damage

To calculate the annual benefits of reducing the damage caused by corrosive water, we multiplied the number of exposed people by the per capita estimate of corrosion damage. All costs are converted to 1985 dollars.

TABLE V-1. Estimates of Annual Per Capita Corrosion Damage (1985 dollars)

Studies	Estimated Annual Corrosion Damage (per capita)			Corrosion Damage Avoidable Through Water Treatment	Annual Per Capita Benefits of Corrosion Control	Assumptions/Notes
	Distribution systems	Residential	Total			
Kennedy Engineers (1973)	$5.57	--	$16 .71*	30%*	$5.01*	Assumed 30% potential reduction in corrosion damage and that distribution costs were one-third of total costs.
Hudson & Gilcreas (1976)	$8.68*	—	$26.04*	50%	$13.02*	They did not include increased operating costs. Per capita estimate assumes 200 million people are served by public water systems. Assumed that distribution costs were one-third of total costs.
Kennedy Engineers (1978)	—	$30.87*	$46. 30*	20%	$9.26*	They calculated $6.17 per capita in savings to residence owners. Assumed residential costs were two-thirds of total costs.
Bennett et al. (1979) (cited in Ryder, 1980)	$9.40	—	$28. 20*	20%	$5.64*	Assumed that 200 million people are served by public water system and that distribution costs were one-third of total costs.
Energy & Environmental Analysis (1979)	$3.98	$7.97	$11.95	38%	$4.54	This is an admitted underestimate: it includes only damage to pipes (not damage to water heaters, increased operating costs, etc.)
Ryder (1980)	$1.17	$22.19	$23.36	25%	$5.84	Ryder ascribed 95% of corrosion damage to private owners.
Kirmeyer & Logsdon (1983)	—	$23 .60*	$35.40*	40%	$14.16*	Assumed residential costs were two-thirds of total damage.
					AVERAGE $8.21 W/OUT EEA $8.82	

* These estimates have been calculated by the authors of this paper. Assumptions are noted above.

Estimates of the population at risk of exposure to corrosive water in the U.S. range from 22.1 million people (Patterson, 1981) to 75.4 million people (Greathouse and Osborne, 1980). Of the available data, we have used the U.S. Geological Survey data on the occurrence of soft water. In 1980, there were 67.7 million people living in areas identified by USGS as having soft and aggressive water.*

Assuming that these people are served proportionately by community and non-community water systems,

$$67.7 \text{ million} \times \frac{219}{240} \text{ million} = 61.8 \text{ million}$$

people would benefit from actions to reduce the corrosivity of their water.

From Table V-1, we have used $8.50 per capita as a point estimate of potential annual savings benefits from water treatment to reduce corrosivity. This is the mid-point of the estimates including the EEA underestimate ($8.21) and excluding it ($8.82). Multiplied by the potentially exposed population (61.8 million) yields annual materials benefits from reduced corrosivity of $525.5 million in 1985 dollars.

For comparison, estimates of average corrosion treatment costs range from under $1 per person per year to about $5 per person per year. The lowest estimates are data collected from 18 cities in six states now known (by EPA) to be treating their water

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* This may somewhat underestimate the real exposure to soft water because many people in hard water areas install water softeners.

to reduce its corrosivity. System size varies from 6,000 to 550,000. Annual capital and operating costs for these cities range from $0.26 per person per year to $1.28 per person per year. System size was not related to per capita cost.

Another estimate, arguably an upper-bound estimate, is from Applegate (1986). This article presented post-treatment requirements, options and associated costs for reverse osmosis (RO)* product water. RO waters are usually extremely corrosive, with pH typically of 5.5-6.9 (Applegate, 1986). Hardness and alkalinity are typically low, also. Applegate calculated average costs for post-treatment of RO product waters for use in municipal drinking water systems. Assuming 100 gallons of water used per person per day, his estimates yield annual capital and operating costs for various processes ranging from $1.28 to $3.03 per person per year.

The highest estimate of annual cost is from EPA's cost estimates (US-EPA, 1984a), for treatment costs for small systems (i.e., serving up to 1000 people). The point estimate, averaging costs for pH adjustment, use of corrosion inhibitors, and stabilizing corrosive water, is a little over $5 per person per year. The range, however, is quite wide and highly sensitive to system size. In some very small systems (i.e., serving 25-100 people), costs may be many times higher.

To be conservative, we used $3.80 as the point estimate of annual per capita treatment costs. This is the arithmetic mid-

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* Reverse osmosis is a technology used primarily for desalinizing sea or other brackish water.

point of the technologies evaluated in US-EPA (1984a), adjusting for number of systems and population served. Multiplying by the 61.8 million people estimated to be receiving corrosive waters produces an annual cost estimate of $234.8 million annually, yielding a benefit-to-cost ratio of over 2:1 for materials benefits, alone. Because the point estimate for treatment costs is probably overestimated, net benefits are probably under-estimated.

These benefits will not be affected by the 1986 Amendments to the Safe Drinking Water Act, which prohibit the use of materials containing lead in public water systems. The estimates in this chapter (both costs and benefits) are based upon the extent of corrosive water in the country, not the population exposed to lead in drinking water.

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APPENDIX A: BOSTON CASE STUDY

THE COSTS AND BENEFITS OF TIGHTENING THE MAXIMUM CONTAMINANT LEVEL FOR LEAD IN DRINKING WATER FROM .05 MG/L TO .01 MG/L: A CASE STUDY OF BOSTON, MASSACHUSETTS

A Policy Analysis Exercise

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EXECUTIVE SUMMARY

This paper reports the findings of the cost/benefit analysis of lowering the maximum contaminant 1 level (MCL) for 1 lead in drinking water to .01 mg/L using the City of Boston as a case study. After discussing the problem of corrosion related lead contamination in general terms and for Boston in particular, my study estimated the costs of additional corrosion control required to lower lead levels in Boston to the contemplated standard, the health benefits resulting from the lower lead levels, and the benefits of reduced materials damage produced by the additional treatment of drinking water.

Although my analysis generated results under different assumptions, the net benefit for the most likely case is $7, 200 , 000 (1985$) in 1988 rising to $8,000,000 in 1992. The Boston share of treatment costs in 1988 is $700,000. On the benefits side, the analysis yielded the following estimates in 1988:

$340,000 for children's health effects,
$190,000 for avoided myocardial infarctions
$115,000 for avoided strokes,
$6,300,000 for avoided deaths, and
$940,000 for reduced materials damage.

In terms of benefit/cost rations, the results are 11.5:1 in 1988 rising to 12.7:1 in 1992. Population growth in Boston accounts for the steady rise in health benefits throughout the period.

In order to account for uncertainties and statistical biases resulting from broth the data employed in the analysis and the exclusion of important categories of health effects (e.g. renal damage, pregnancy complications, and cardiovascular disease in other age groups and in blacks), sensitivity analysis was per formed. Even under a pessimistic set of assumptions, additional treatment would still yield positive net benefits. Using optimistic assumptions, the case for lowering the MCL for lead is overwhelming (net benefits = $11.5 million in 1988).

The results of the analysis suggest that EPA should take the following actions:

1. Lower the maximum contaminant lever for lead from .05 mg/L to .01 mg/L. The agency should consider waivers in exceptional cases.

2. Provide technical assistance and information to localities to aid them in their efforts to control corrosion thereby reducing levels of lead and other contaminants in drinking water.

INTRODUCTION

Since Roman times, people have known about some of the toxic effects of human exposure to lead. Despite these concerns, lead has continued to be used for a variety of purposes: as an additive in paint and gasoline and as a material for water conveyance pipes. It was not until recently, however, that governments have taken action to reduce environmental exposure to lead. In the United States, the use of lead based paint was banned. The federal government also regulated the use of lead as an additive in gasoline beginning in the early 1970s. Among toxic substances, lead was one of the first for which exposure standards were established.

Increasingly, research has indicated that physiological and neurophysiological damage can result from exposure to levels previously thought to be safe. In light of this evidence, the Centers for Disease Control (CDC) lowered the criteria for lead poisoning in children from 30 ug/dl to 25 ug/dl (when coupled with free erythrocyte protoporphyrin (FEP) of 35 ug/dl). It has motivated the EPA to propose a phase out of the use of leaded gasoline. In response to the growing concern about low-level exposure to lead, EPA also has proposed that the MCL for lead be lowered to .01 mg/L.

While lead can be found in both ground and sur face water supplies, the major source of contamination of drinking water is the leaching of lead from water distribution pipes and household

plumbing by corrosive water. Treatment methods now being used in some communities have reduced lead concentrations below the current MCL of .05 mg /L. If a new, lower standard is adopted, though, additional treatment may be required even in communites currently undertaking treatment.

As part of the regulatory process, the agency has examined the costs and benefits of water treatment for the country as a whole. To corroborate these analyses and examine the costs and benefits in a more systematic fashion the Office of Policy Analysis has undertaken case studies of several cities. As a part of this effort, I was asked by that office to perform a cost/benefit analysis for Boston, a city which has highly corrosive water and whose water distribution System is representative of older urban areas.

After describing the general problem of lead and corrosion and potential treatment methods, this study will look at Boston's situation and its history of corrosion control. The analysis itself will begin with an examination of the additional treatment likely to be employed in Boston and its crest. It will then turn to the benefits. Because of data and epidemiological constraints, the benefits analysis is limited to avoided costs associated with neurological damage in children, hypertension and related cardiovascular disease in adult white males, aged 40-59, and reduced materials damage. This paper will conclude with a

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1 U. S. Environmental Protection Agency. "Regulating Corrosive Water". Office of Planning and Evaluation, April 1981, p.2.

comparison and discussion of the costs and benefits and recommendations.

BACKGROUND

The problem at hand stems from the unfortunate coincidence of highly corrosive water and the use of piping materials containing substances which, when leached, contaminate drinking water. While this analysis is primarly concerned with the health impacts of lead and general materials damage corrosive waters may also contribute other substances including, cadmium, asbestos, iron, and copper to drinking water.

Despite our longstanding knowledge that lead is harmful to human health, several characteristics have made it popular as a material for water piping. It is easy to form, cut and join. It is also durable and resistant to subsidence and frost. Because of its durability, many lead pipes installed in the early part of this century are still in use. In addition, a number of building codes still allow its use for joining conveyance pipes.

Lead can be found at many points between the water source and the consumers' tap. Although utilities once used lead lined water mains, many of these have been replaced. Currently, a major source of concern is the use of lead in sevice lines, the

2 American Water Works Association (AWWA), Internal Corrossion of Water Distribution Systems: Cooperative Research Report, 1985, p. 214.

3 U.S. EPA, "Statement of Basis and Purpose for Amendments to the National Interim Primary Drinking Water Regulations", Office of Drinking Water, 1980, p. 48.

piping which connects a building's plumbing with the main. While many of these pipes have been replaced over the years, a large number remain in use. Lead can also be found in goosenecks, caulking, gaskets, solder and plumbing fixtures.

Although solder and plumbing fixtures constitute proportionally a small amount of interior surface area, studies halve shown that these sources can contribute a significant proportion of the lead found in drinking water. A British study in 1977 found lead levels in houses without lead pipes as high as those found in lead plumbed houses.[5] These results were confirmed by a second study by Lyon and Lenihan who collected water samples from a modern office building with lead based solder but no lead plumbing. Forty four percent of the samples exceeded .1 mg/L.[6] Studies also show that while lead levels decrease rapidly with the age of the soldered joints, contamination will persist for many years.[7] Laboratory studies have corroborated these findings and have also demonstrated analogous problems for brass and bronze plumbing fixtures.[8]

These results are a cause of concern. While the incidence of lead in service lines, mains, and internal plumbing has

4 Karalekas, P. et al., ''Lead and Other Trace Metals in Drinking Water in the Boston Metropolitan Area", Proceedings AWWA 95th Annual Conference, Minneapolis, Minnesota June 9-12, 1975, p. 7.

5 AWWA, Op. cit., p. 215

6 Ibid., p .216

7 Murrell, Norman, " Impact of Metallic Solders on Water Quality", Specialty Conference on Enviromental Engineering, EE Division, ASCE/Boston, MA, July 1-5, 1985.

8 AWWA, Op. cit. , p. 222

declined, the vast proportion of building plumbing systems still use lead-based solder. This fact suggests that lead may be a problem wherever water is corrosive, not only in older urban areas where lead plumbing and service lines can still be found. In fact, newly soldered joints will contribute lead even in areas where water supplies are not corrosive.

The other part of the problem is corrosive drinking water supplies. A large number of water utilities supply corrosive water. In two studies, one by Millette and the other by the Midwest Research Institute (MRI), river two-thirds of the utilities sampled reported distributing water that is either moderately or highly corrosive Millette's study examined 130 utilities serving more than 40 million people. The MRI sample included 388 utilities serving more than 103 million people. [9]

A number of factors contribute to the corrosive nature of water. Among them are low pH, alkalinity, hardness, dissolved oxygen, dissolved solids, velocity and temperature.[10] Contaminant levels are also greatly affected by the length of time that the water is in contact with sections of pipe. When water has been standing in the service line and internal plumbing, it tends to produce higher levels of contaminants.[11] An important characteristic that affects corrosivity is the hardness of water, that is, the concentration of calcium

9 U.S. EPA, "Statement of Basis and Purpose for Amendments to the National Interim Primary Drinking Water Regulations", pp. 37-40.

10 U.S. EPA, "Regulating Corrosive Water" p.3.

11 U.S. EPA "Statement of Basis and Purpose for Amendments to the National Interim Primary Drinking Water Regulations", p.31.

carbonate ($CaCO_3$). In hard waters, where high concentrations of $CaCO_3$ are present, a protective skin forms along the inner walls of pipes. [12] Soft water tends to be corrosive because the $CaCO_3$ concentration is low which inhibits the information of the protective film. [13]

Before discussing the various methods currently available to lower lead levels, I would like to briefly discuss the kinds of health effects associated with exposure to lead. Lead has long been implicated for its damage to the brain and the central nervous system. At low-level exposure, the concern is especially great for children who retain proportionally greater amounts of lead and who are also going through critical stages in the development of the brain and cognitive abilities, making them even more vulnerable. [14] Studies show that exposure to lead may cause anemia and renal damage; at high levels, it can result in encephalopathy and death. [15] Researchers have also demonstrated a negative relationship between blood lead levels and IQ. In addition, epidemiological studies have demonstrated a relationship between elevated lead levels in pregnant women and low-level fetal malformations. Elevated blood lead levels in pregnant women also may lead to still births and miscarriages. [16]

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12 Ibid., pp. 31-32

13 Ibid., p.35

14 U.S. EPA. "Regulating Corrosive Water", 1981, p.6.

15 Ibid., p.6.

16 U.S EPA, Costs and Benefits of Reducing Lead in Gasoline, 1985, chapter IV.

Studies from the mid-1970's have suggested what there is a relationship between soft water and cardiovascular disease (CVD). While some evidence indicates that the mechanism for this is soft water's deficiency in magnesium and calcium, substances that may have a protective effect on blood pressure leachate contaminants common is soft water such as lead can increase blood pressure, and with it, the incidence of CVD. [17] In fact, epidemiologists have uncovered a very strong relationship between blood lead levels and blood pressure. According to a study by Pirkle et al., a 37% drop in blood lead was associated with a 17.5% reduction in cases of hypertension and lower rate of CVD. [18]

Short of the wholesale replacement of distribution pipes, water utilities can lower lead concentrations by controlling corrosion. Control techniques currently used include pH adjustment, hardening, and the addition of silicates or phosphates. The choice of method depends upon both the characteristics of the water and the types of materials used in the distribution system. [19]

Adjusting pH is a widely used method to treat corrosive water. Most utilites that adjust pH use lime. In addition to raising pH, lime increases alkalinity and the hardness of water. The high concentration of calcium promotes the formation of the

17 U. S. EPA, "Statement of Basis and Purpose for Amendments to the National Interim Primary Drinking Water Regulations", p. 45.

18 Pirkle et. al., "The Relationship Between Blood Lead Levels and Blood Pressure and its Cardiovascular Risk Implications", American Journal of Epidemeology, 1985, 121:246

19 U. S. EPA, "Statement of Basis and Purpose for Amendments to the National Interim Primary Drinking Water Regulations", p.26.

protective $CaCO_3$ film. With respect to the dissolution of lead, pH adjustment facilitates the formation of an insoluble lead precipitate that adheres to the inner walls of pipes and prevents metallic lead from being further attacked. [20] The American Water Works Association (AWWA) cites laboratory studies indicating that lead dissolution approaches a minimum when pH approaches 9.[21]

Corrosion can also be controlled with the use of corrosion inhibitors (e.g. zinc orthophosphate), chemical additives which help form a protective film. While phosphate treatments have been used for over a decade, intensive research has taken place in only the last several years. These studies indicate that treatment with zinc orthophospate is effective, but only within certain pH and alkalinity constraints.[22]

Aside from lowering lead concentrations, corrosion control has lowered the levels of other contaminants and reduced damage to water pipes and other distribution system components. As A result, any analysis of the costs and benefits of corrosion control must not only consider the benefits from reduced exposure to, lead but also from the reduced exposure to other contaminants, avoided materials damage and improved aesthetics.

Cadmium, another material found in distribution pipes and leached by corrosive water is also linked to hypertension. It is found at high levels in hypertensive and has induced

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20 Karalekas, ''Alternative Methods for Controlling the Corrosion of Lead Pipe", Journal of the New England Water Works Association, June 1978, p. 2.

21 AWWA, op. cit., P.243

22 Ibid., pp.246-260.

hypertension in animal studies.[23] Cadmium also may cause irreversible renal damage.[24] Concern also has been expressed over the use of asbestos lined concentrate pipes. While asbestos is a known carcinogen when inhaled, its health effects when ingested have not been well defined. [25] Because asbestos pipe is not used in Boston and cadmium levels are acceptably low, contamination from these substances was not examined in this analysis.

In addition to the contaminants regulated by primary standards, there are substances subject to secondary standards that also are leached from pipes. These include iron and copper. EPA regulates cropper on the basis of smell and taste. concentrations greater than the 1 mg/L standard may also stain sinks and porcelain. Likewise, iron is also regulated on the basis of aesthetic considerations. [26]

Finally, corrosive water damages pipes and other components with which water comes in contact. The process of leaching minerals causes more rapid interior degradation of both distribution pipes and privately owned plumbing pipes, making them more susceptible to leakage and rupture. [27] Leakage from distribution systems may be substantial, sometimes accounting for

23 U.S. EPA, "Regulating Corrosive Water", p.8.

24 U.S. EPA, "Statement of Basis and Purpose for Amendments to the National Interim Primary Drinking Water Regulations", p. 44.

25 U.S. EPA, "Regulating Corrosive Water", p.8.

26 Bureau of Water Works, Portland, Oregon, Internal Corrosion Mitigation Study: Final Report, 1982. p.5-12.

27 U.S. EPA, "Regulating Corrosive Water", p.13.

33% of the water supply.[28] In addition, corrosion promotes tuberculation, a process in which leached materials build up on the inner walls of pipes reducing their carrying capacity. [29] This deterioration leads to reduced flow and the need to increase pumping on the part of the utility. Various studies have shown that the crests of corrosion damage are substantial.

BOSTON: ITS WATER AND CURRENT TREATMENT

The water supplied to Boston by the Massachusetts Water Resources Authority (MWRA), the regional 'wholesale' water utility, is among the most corrosive in the country. It is relatively acidic with a pH of 6.7, and soft with hardness measured at 12 mg $CaCO_3/L$. Alkalinity is low as well.[30] Boston is also city with an old distribution system and housing stock and has a significant number of lead services still in existence Although local officials have long recognized the dangers inherent in the use of lead pipe for supplying potable water and have commenced the systematic replacement of lead services, property owners are responsible for that portion of the service line that runs from the property line to the structure. As a result, staff engineers at the Boston Water and Sewer Commission

28 U.S. EPA, "Statement of Basis and Purpose for Amendments to the National Interim Primary Drinking Water Regulations", p.27.

29 U.S. EPA, Regulating Corrosive Water, p.13.

30 Karalekas et. al., "Control of Lead, Copper and Iron Pipe Corrosion", Journal of the American Water Works Association. 1983, p.93.

(BWSC) estimate that 44% of their residential customers still have lead services. [31]

Some studies, however, indicate that the lead problem could be even more widespread. The most comprehensive tap water sampling in Boston indicated that 70% of the household showed evidence of lead dissolution. [32] Since only half the houses in the survey had lead services, we must assume that lead is being leached out from other sources. From the previous discussion concerning lead solder's contribution to lead levels in drinking water, it seems likely that solder accounts for much of the contamination. Goosenecks and caulking also contribute lead.

Because of the widespread existence of lead in piping material, tap water was extensively monitored in the mid 1970's. This study revealed a large proportion of samples in excess of the. 05 mg/L MCL . [33] In addition, a study by Worth et al. showed a statistically significant relationship between lead in tap water and blood lead in children. [34] In response to this situation, the Metropolitan District Commission (MDC), the former water supply agency, began treating the region's water.

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31 BWSC staff engineers, January, 1986.

32 Karalekas, "Lead and Other Trace Metals in Drinking Water in the Boston Metropolitan Area", p. 7.

33 Ibid., p. 13.

34 Worth et. al. "The Contribution of Household Tap Water to Blood Lead Levels", U.S. EPA grant # R-802794, 1981 p.20.

At first, the MDC used zinc orthphosphate but was unsuccessful.[35] (It now seems that the failure of orthophosphate was due to the low pH of Boston's water.[36]) Beginning in 1977, the MDC began pH adjustment using sodium hydoxide (NaOH), a control technique that has proven to be extremely effective. The MDC chose NaOH over lime because its consultant, Metcalf and Eddy, estimated that capital and operating and maintenance costs were significantly lower for NaOH treatment.[37] In addition, sodium levels in MDC water were sufficient low that adding sodium would not create a health problem.[38]

Monitoring performed by EPA's Region I office from 1976 to 1981 indicated that lead, iron and copper levels dropped significantly.[39] More importantly, lead levels in most water samples fell below .05 mg/L. Most samples, however, had levels which remain above the contemplated .01 mg/L MCL. Compliance with the proposed standard will require corrosion control to further reduce lead levels in Boston's drinking water.

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35 Karalekas, Control of Lead, Copper, and Iron Pipe Corrosion", p. 94.

36 Discussion with Peter Karalekas and studies reported in the AWWA corrosion control study, December, 1985

37 Discussion with Peter Karalekas, April,1986.

38 Ibid.

39 Karalekas, "Control of Lead, Copper, and Iron Pipe Corrosion", p. 93.

PROPOSED TREATMENT AND ITS COST

The primary objective of additional corrosion control is to reduce lead concentrations in order to comply with the proposed .01 mg/L standard. Before deciding upon which treatment methods would be appropriate we must first establish the criteria by which we define compliance with the standard. Based on recent epidemiological studies and technical feasibility, this analysis proposes the following compliance criteria. First, the MCL should be based on the standing grab sampler that is, the sample which is taken immediately after turning on the cold water tap and the one which is statistically the best predictor of blood lead levels. Second, compliance should be based on tap water collected from a sample of worst case households, those which have new lead soldered joints, lead services, or other evidence of lead pipes. Because it is impressible to guarentee that every household could meet the .01 mg/L standard even using state of the art corrosion control techniques, we should use the mean concentration generated by this sample.

We must also be cognizant of a number of uncertainties concerning the effectiveness of corrosion control techniques. A particular form of treatment might produce excellent results in one system, and yet, performance in another may prove less effective. In addition, some methods have been extensively tested in the lab but not in the field. The treatment methods I will discuss are endorsed by the new AWWA manual on corrosion control. They also have been suggested as the likely

alternatives by engineers at EPA Region I and the MWRA and have proven effective in other New England cities where the characteristics of the water and the distribution systems are similar. Nevertheless, our estimates of expected reductions in lead concentrations are based only on educated judgements.

After reviewing the current research literature on corrosion control, and discussing the Boston situation with EPA and MWRA personnel, it is likely that additional treatment would consist of two stages.[40] First, MWRA would further raise pH by increasing the NaOH concentration. When the MDC first began NaOH treatment, the state of the art suggested that pH should be elevated to a range of 7 to 8 or higher. Currently the pH of treated water is 8.5. Recent findings, however, indicate that corrosion control will be even more effective when pH is raised to 9.

In addition it is likely that the utility would take action to achieve consistent pH levels through out the complex web of the MWRA distribution system.. This would necessitate the installation of several additional pumping stations to even out the concentration of NaOH throughout the delivery system.

While additional and better controlled pH adjustment should reduce corrosion, the use of a corrosion inhibitor will probably be necessary. Zinc orthophosphate is the likely alternative. Although this method was used unsuccessfully before in Boston, it now seems that pH was too low. When used in a

40 Discussions with Peter Karalekas of EPA and Guy Foss of the MWRA Mr. Foss was reluctant to make any judgements but indicated that higher pH and zinc orthophosphate was a likely scenario, December 1985.

higher pH environment corrosion control experts believe that orthophosphate will be very effective. In addition, the MWRA does not expect a repeat of the phosphate induced algae growth experienced in 1976 in the smaller storage reservoirs because they are no longer used, a level that would comply with the contemplated MCL. [41]

Like Boston, Bridgeport, Connecticut also has low pH water supplies and widespread use of lead in the distribution system. Using lime to raise pH and zinc orthophosphate, water quality authorities in Bridgeport have successfully reduced corrossion. Samples for lead indicate a mean concentration of .007 mg/L overall and .01 mg/L for the standing grab sample. [42]

The technologies associated with corrosion control are relatively simple and the costs are calculable. Most treatment methods employ processes similar to those used for chlorination and fluoridation. The chemicals are held in storage tanks, mixed with water, and then pumped into the distribution system. Thus, the capital component includes the costs of storage tanks, mixing equipment, pumps and installation labor. Operating and maintenance costs (O&M: labor, energy, repairs) are moderate. Usually they amount to approximately 20% of the capital outlays. The expenditure for chemicals constitutes the largest component for any kind of corrosion control treatment with lime being the cheapest and zinc orthophosphate among the most expensive.

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41 Guy Foss, MWRA .

42 Karalekas, "Alternative Methods for Controlling the Corrossion of Lead Pipe", pp.7-9.

The pH adjustment phase of the additional treatment can be broken down into two components: additional pumping stations and an increased chemical feed rate. Because of the low buffering capacity of Boston's water, only a small increment to the feed rate will be necessary to raise the pH to the desired level. Both the EPA and MWRA estimate that chemical costs would increase by approximately 10%. Because NaOH is a by-product of automobile manufacturing and output varies directly with automobile output, its price has fluctuated dramatically. Based on the average price for the last five years, the cost of NaOH is $.54 per mg per million gallons (mg/MG, 1985$).[43] At that price, raising chemical costs by 10%. would amount to an annual incremental increase of $85,000 (1985 $; all costs and benefits in this paper are in 1985 $ unless otherwise specified), assuming an average flow of 310 million gallons per day (MGD).

The cost of an additional two 50 MGD NaOH feed systems including installation is $150,000.[44] Amortized at 5% over 20 years, the resulting annual capital cost is $12,000. Operating and maintenance costs are $30,000 (20% of $150,000). Therefore phase I would cost approximately $127,000 per year. (See TABLE I for a Summary of treatment crests.)

Although the per unit chemical cost for zinc orthophosphate is much higher, its feed rate tends to be low. While the literature cites several different cost estimates, this study

43 NaOH cost figures supplied by the MWRA.

44 U.S. EPA, "Corrosion Manual for Internal Corrosion of water Distribution Systems", Prepared for the Office of Drinking Water by Environmental Science and Engineering, Inc., 1984, p. 103.

TABLE I

TREATMENT COSTS

PARAMETERS			
average flow	310		
interest rate	5%		
payback period	20		
CRF	0.08024		
NaOH			
cost (mg/MG)	$0.54		
feed rate (mg/L)	1.4		
		chemicals	$85,541
		O&M	$30,000
		capital	$12,036
		total	$127,578
Zinc Orthophosphate			
EPA (A)			
cost (mg/MG)	$5.44		
feed rate (mg/L)	2		
		chemicals	$1,231,072
		O&M	$34,000
		capital	$13,641
		total	$1,278,713
EPA (B)			
cost (mg/MG)	$5.44		
feed rate (mg/L)	3		
		chemicals	$1,846,608
		O&M	$34,000
		capital	$13,641
		total	$1,894,249
Tech Products			
cost (mg(ZN)/MG)	$21.00		
feed rate (mg(ZN)/L)	0.6		
		chemicals	$1,425,690
		O&M	$30,000
		capital	$12,036
		total	$1,476,726

TABLE I (cont.)

AWWA

cost (mg(Zn)/MG)	$19.20
feed rate (mg(Zn)/L)	0.5

chemicals	$1,086,240
O&M	$30,000
capital	$12,036
total	$1,128,276

Total

EPA (B)	$2,021,827
TECH PROD	$1,595,304
EPA (A)	$1,406,291
AWWA	$1,255,854

uses the figures provided by Technical Products, a chemical firm which manufactures orthophosphate and supplies as the feed systems. Assuming a flow of 310 MGD and a feed rate of .6 mg/L, the annual chemical cost is $1,425,000 based on a unit cost of $21 per mg of zinc per million gallons (mg(Zn)/MG).

The cost of the zinc orthophosphate feed systems are less than those for NaOH systems which 100 MGD plant costing $30,000. In order to meet peak demand, the MWRA would require a total of 500 MGD capacity costing $150,000 of $12,000 on an annual basis. Based on these capital requirements, the expected annual O&M costs are $30,000. The total annual cost for zinc orthophosphate treatment is therefore $1,468,000. The combined annual cost of pH adjustment and orthophosphate is approximately $1,600,000.

While this cost figure represents the most likely case, there are a number of factors which could lower treatment costs. First, additional pH adjustment alone could be sufficient. Secondly, optimal pH for zinc orthophosphate could require a lower NaOH feed rate and with it, lower NaOH chemical costs. Finally, these costs are based upon MWRA's projected demand of 310 MGD, a forecast which disregards price responses (i.e. if water rates increase, consumers may reduce their demand). Because of the capital requirements of the Boston Harbor cleanup program, combined water and sewer rates are expected to double in real terms over the coming decade with probable reductions in demand. Since corrosion control treatment costs are heavily dependent on flow, price induced water conservation would lower treatment costs.

HEALTH BENEFITS

Despite the fact that the health effects from exposure to lead are relatively well understood, monetizing health benefits is complicated and requires a number of stages and several kinds of data. In graphic terms, the process is a chain which starts with a change in contaminant concentration producing a change in exposure which produces a change in body lead burden, which finally results in observable physiological and neurological changes. By reducing contaminant concentrations, we can reduce the adverse health impacts of exposure to lead and avoid the various costs associated with them.

The first requirement of this stage of the analysis therefore, was data for a change in water lead concentration. based on the definition of compliance established earlier in this analysis and the Region I water lead data, we estimated the reduction in lead concentrations. The mean concentration for the standing grab sample was .032 mg/L. This value is based on the cross sectional data pooled for the last five months in which samples were taken. During this time lead levels seemed to stabilize following the commencement of NaOH treatment. Since compliance by definition requires that we lower the mean concentration to .01 mg/L, lead levels would drop by .022 mg/L on average. Assuming proportional reductions, the decline in lead concentrations ranges from .05 mg/L to .0055 mg/L for the households in the sample.

Because the sample size is so small, it is likely that this reduction in water lead in not representative of tap water throughout Boston. In fact, we know that the houses in the study were se1ected because they had lead services, a characteristic true of only 44% of residential consumers. The standing draw data used here, though, is the water that is in contact with internal plumbing. Because of this fact, the fact that 70% of the households surveyed (only 50% of which had lead service) in 1975 showed evidence of lead dissolution, and the studies which show that lead solder contributes significant amounts of lead to drinking water, it is likely that the data are representative of a much larger portion of the Boston housing stock. Therefore, in the most likely case, this analysis uses a figure of 57% (the average of 44% and 70%) to calculate the number of households effected by further reductions in drinking water lead levels.

Second, the analysis required blood lead data for the relevant segments of the population, children and adult white males, aged 40-59. In Boston, only children are monitored for blood lead. This data, however, were not useful since it was collected and organized for a completely different purpose. Consequently, this analysis employed data from the National Health and Nutritional Examination Survey (NHANES II). By using national data, however, we are making the assumption that the Boston population groups have the same blood lead distribution as the nation as a whole. But because an Urban population is likely to have blood lead levels higher than the national average, the analytical results will be biased. The blood lead

data also had to be adjusted for changes in gasoline lead content so that we can isolate the impact of a change in water lead concentrations.

Thirdly, we had to have population estimates for the 1985-1995 period. The population projections employed in this study are based on the Census Bureau's estimates and reveal several patterns which are significant to this analyis.[45] (Although Boston's population had declined for most of the post-war era, this trend reversed in this decade. Population increases are most pronounced for the two groups studied in this analysis. The number of young children is expected to grow rapidly as the baby-boomers start to have children. In addition, the ranks of adult white males, aged 40-59 will swell over the next decade as the baby-boomers age.

Finally, when estimating health benefits, this analysis Assumes that the proposed MCL will not be implemented until at least 1988. Thus, the calculations reflect benefits starting in that year and extending out to 1992.

CHILDREN'S BENEFITS

In order to calculate the health benefits for children, resulting from reduced exposure to lead in drinking water, the analysis used a methodology similar to that employed in EPA's

45 Boston Redevelopment Authority, "Population Projections for Boston and for Boston City Hospital Neighborhoods--by Race,Ethnicity, Age, Income, and Pverty Status--to the Year 2000, Research Department, 1985, pp.41-44.

study of lead in gasoline. The derivation of avoided costs is based on the number of children whose blood lead level falls below 25 µg/dl as the result of reduced lead concentrations in drinking water. We can estimate this number by taking the difference between the number of children with blood lead >25 µg/d at current lead levels in drinking water and the predicted number of children with blood lead >25 µg/dl at lowered lead levels in drinking water.

In the first step, children were broken into two racial groups, black and non-black, and into seven two-year age groups starting with six months to the second birthday and ending with twelve to thirteen years of age.[46] MINITAB, a statistical software package, was then used to generate a distribution of blood lead levels for each age/race group based on the parameters of the NHANES II data, controlling for gasoline lead levels..

In order to estimate the change in the distribution of blood lead for each group, we had to relate reduced exposure levels as measured by lower lead levels in drinking water to blood lead levels. This analysis uses a 1983 study by Ryu which established the relationship between water lead and blood lead in children as depicted in the following equation:

$$PbB = a + .12PbW$$

where:

PbB = blood lead in µg/dl;
a = the constant plus other demographic and other environmental factors; and
PbW = water lead in µg/L (standing grab sample).

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46 Children were categorized in this way because blood lead distributions are heavily dependent on age and race.

Based on this regression equation and the data on water lead reduction, a child in Boston is subject to a possible reduction in blood lead ranging from .66 µg/dl to 6.04 µg/dl depending on the reduction in water lead in his/her household.

In the final step, a BASIC program used the initial blood lead distributions and epidemiological relationship above to simulate the change in the blood lead distribution for each age/race group. Using the before and after distributions, the program calculated the probability that a child's blood lead would drop below 25 µg/dl. By applying that probability to the number of children in an age/race group and repeating the process for all 14 groups, this procedure estimated that additional treatment of Boston water will reduce the number of lead-poisoned children by 87 in 1988 (see Table 11).

In terms of medical and compensatory education expenses, EPA believes that $3,900 can be saved for each avioded case of lead poisoning $1,100 for medical treatment and $2,800 for education. Therefore we can expect a total of $340,000 in benefits for children in 1988, rising to $349,000 in 1992.

This estimate, however, merits closer scrutiny. Several factors suggest that it is somewhat conservative. First, the NHANES II data probably underestimates blood lead levels for Boston children. Urban children are exposed to higher amounts of lead (automobile exhaust, lead paint, dust, industrial sources) and are therefore more likely to have higher blood lead levels. By using national data, we start out with proportionally fewer individuals with blood lead >25 µg/dl thus reducing the

TABLE II

CHILDREN'S BENEFITS

AMETERS
efit per capita $3,900
ent applicable 54%

BLACKS

AGE GROUP	POP	% CHANGE 25 ug/dl	NUMBER CHILDREN	BENEFITS 1988	POP	BENEFITS 1989	POP	BENEFITS 1990	POP	BENEFITS 1991	POP	BENEFITS 1992
-2yr	4274	0.530%	12.2	$47,706	4329	$48,319	4385	$48,944	4390	$49,000	4396	$49,067
2-3	5717	0.715%	22.1	$86,086	5772	$86,914	5850	$88,089	5855	$88,164	5861	$88,254
4-5	5350	0.705%	20.4	$79,433	5384	$79,938	5416	$80,413	5467	$81,170	5495	$81,586
6-7	4984	0.310%	8.3	$32,539	4995	$32,610	5001	$32,650	5078	$33,152	5143	$33,577
8-9	4618	0.085%	2.1	$8,267	4607	$8,247	4579	$8,197	4690	$8,396	4784	$8,564
10-11	4251	0.000%	0.0	$0	4218	$0	4163	$0	4292	$0	4422	$0
12-13	3885	0.005%	0.1	$409	3830	$403	3746	$394	3907	$411	4070	$429
-TOTAL			65.2	$254,439		$256,432		$258,687		$260,294		$261,477

NON-BLACKS

AGE GROUP	POP	% CHANGE 25 ug/dl	NUMBER CHILDREN	BENEFITS 1988	POP	BENEFITS 1989	POP	BENEFITS 1990	POP	BENEFITS 1991	POP	BENEFITS 1992
-2yr	7277	0.135%	5.3	$20,689	7371	$20,956	7466	$21,227	7475	$21,252	7484	$21,278
2-3	9734	0.145%	7.6	$29,725	9828	$30,012	9960	$30,415	9970	$30,445	9979	$30,473
4-5	9110	0.120%	5.9	$23,023	9167	$23,167	9223	$23,308	9308	$23,523	9356	$23,644
6-7	8486	0.065%	3.0	$11,616	8505	$11,642	8514	$11,655	8647	$11,837	8757	$11,987
8-9	7862	0.000%	0.0	$0	7844	$0	7796	$0	7985	$0	8146	$0
10-11	7239	0.000%	0.0	$0	7182	$0	7088	$0	7308	$0	7529	$0
12-13	6615	0.000%	0.0	$0	6521	$0	6379	$0	6653	$0	6930	$0
-TOTAL			21.8	$85,053		$85,778		$86,605		$87,058		$87,383
TAL			87.0	$339,492		$342,210		$345,292		$347,351		$348,859

probability that a blood lead level will fall below the CDC blood lead level criteria for lead poisoning.

Secondly, the methodology employed in this analysis implicitly assumes that water lead and blood lead are independent of each other. This ignores the fact that higher blood lead levels are the result of greater exposure to lead, and probably, people who have higher blood lead levels are more likely to have higher lead lead levels in their drinking water. A more realistic methodology would produce a higher probability that a child falls below 25 μg/dl because it would assign the larger reductions in lead exposure from drinking water to high lead children when simulating the new blood lead distribution. Under the independence assumption, however, high lead individuals face the same reductions as low lead individuals, reducing the probability of falling below 25 μg and biasing down the benefit estimates.

Finally, and most importantly, the monetary estimate comprises only avodied medical costs associated with the treatment of lead poisoning and avoided expenses for compensatory education. A number of benefit categories have been excluded from the analysis because the relationship between blood lead levels and certain health effects have yet to be precisely specified. Such benefits include avoided costs associated with renal damage, a very serious effect of lead exposure, increased risk of anemia, vitamin D deficiency, and permanent nerve damage. The analysis also includes benefits that are exceeding difficult to quantify such as avoided pain and suffering associated with

medical care and reduced quality of life resulting from the permanent effects of damaged cognitive development.

HEALTH BENEFITS -- ADULT WHITE MALES, AGES 40-59

Although the public health community has long known about the link between high lead exposure and elevated blood pressure, it is only recently that research has uncovered effects at low levels of exposure. Prior to the analysis of the NHANES II data by CDC and EPA personnel, a number of investigations reported a statistically significant relationship between low to moderate blood lead levels and blood pressure in males. In addition to epidemiological analyses, animal studies also demonstrate this link.[47] The research also indicates possible causal pathways by which lead acts on the cardiovascular system. These include renal changes and inhibited uptake of calcium, an element which suppresses blood pressure. Besides demonstrating a strong and significant relationship between blood lead levels and blood pressure, the analysis of the NHANES II data showed that there was no threshold level of exposure. In other words, there are blood pressure effects at any blood lead level down to zero.[48]

Because of lead's direct contribution to hypertension, the toxin is also associated with cardiovascular disease (CVD) resulting from elevated blood pressure. Two extensive studies,

47 U.S. EPA Costs and Benefits of Reducing Lead in Gasoline, pp.V-4 - V-5.

48 Ibid., pp.V-6 - V-15.

the Framingham and the Pooling Project, have assessed the risk of CVD (strokes, myocardial infarctions, and deaths resulting from all forms of CVD) based on several important variables, including blood pressure, serum cholesterol, and smoking. The corresponding risk regression equations show a very strong relationship between CVD and blood pressure. [49] Since blood pressure seems to increase with blood lead, so too will the incidence of CVD.

To calculate reduced cases of hypertension and incidence of CVD, we must determine the impact of lower lead exposure from drinking water on blood lead levels in adult men. While a number of epidemiological studies have been performed which relate water lead to blood lead in adults, the Pocock study is perhaps the best. His study is especially relevent to this analysis because it measures effects at lower water lead concentrations. His findings are summarized in the following equation:

$$PbB = a + 0.6PbW$$

where:

PbB = blood lead in µg/dl
a = constant plus other demographics and environmental factors, and
PbW = water lead in µg/L (standing grab smaple).

Using this regression equation and the estimate of reduction in water lead levels, the mean reductions in blood lead is estimated to be 1.33 µg/dl (.06 * 22.2 µg/L). Accounting for changes in gasoline lead, blood lead for the average male will decline from 8.25 µg/dl to 6.92 µg/dl in 1988.

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49 Ibid., pp V29 - V - 31.

Hypertension

Medical authorities consider adults having diastolic blood pressure greater than 90 to be hypertensive. Elevated blood pressure dramatically increases the risk of all forms of cardio-vascular disease and thus requires medical attention. Treatment costs for hypertension include visits to a physician, medication, hospital stays, and the opportunity costs of lost working days, and when combined, total $250 per year. [50]

While, calculating the reduction in cases of hypertension for adult males employs on a fairly direct method, the process in this analysis is complicated by that fact that the logistics regression developed by Pirkle and Schwartz (1985), which estimates the probability that an adult male will be hypertensive, performs poorly at blood lead levels <10 µg/dl . Consequently, this analysis does not make a quantitative estimate. While it is likely that there will be a reduction in cases of hypertension, the number will be small and the omission will not seriously affect the outcome of the analysis. It is, however, one of the factors which contribute to a conservative estimate of the benefits.

Cardiovascular Disease

Having previously estimated the reduction in blood lead resulting from reduced lead levels in drinking water, calculating

50 Ibid., p. V-38

the reduced incidence of CVD requires that we first estimate the change in blood pressure, and second, estimate the change in risk of suffering from various forms of CVD.

By using the before and after blood lead values (i.e. 8.25 µg/dl and 6.92 µg/dl) in the NHANES II regression equation linking blood lead and blood pressure, we calculated the change in blood pressure. We then used the before and after blood pressure values in the CVD risk regression equations in order to estimate the change in probability that an individual will suffer from CVD. By applying the changes in probability to the adult white male population we were able to estimate the avoided incidence of CVD. (See table III)

Myocardial Infarctions. In this analysis, the benefit estimate for Myocardial Infarctions (MIs) is based on an EPA Calculation that includes medical costs (both physician and hospital) as well as lost wages. [51] Although fatal MIs are included, the benefits measure in this category does not account for the value of a lost life. This valuation is treated in a later section.

The estimate of avoided MIs is based on the Pooling Project's risk assessment in which the probability of suffering a MI was calculated as a function of age, smoking behavior, serum cholesterol and diastolic blood pressure. We derived the change in the probability of suffering an MI from the change in blood pressure. Multiplying the probability differential by the population yields the estimate that 2.95 MIs can be avoided in

51 Ibid., p. V-38.

TABLE III

ADULT BENEFITS

PARAMETERS

serum cholesterol	218
average age	50
Baseline blood pb	17.4
blood pb reduction	1.33
percent applicable	54%

AVOIDED MYOCARDIAL INFARCTIONS

PARAMETERS

avoided cost per MI	$65,600
smoking	0.8

	1900	1989	1990	1991	1992
start blood lead	8.25	8.23	8.22	8.20	8.19
end blood lead	6.92	6.90	6.89	6.87	6.86
start blood pressure	81.53	81.51	81.51	81.50	81.49
end blood pressure	80.72	80.70	80.70	80.68	80.68
start prob MI	0.00658	0.00658	0.00658	0.00658	0.00657
end prob MI	0.00643	0.00643	0.00643	0.00642	0.00642
Dif prob MI	0.00015	0.00015	0.00015	0.00015	0.00015
population	36100	36800	37500	38800	40250
avoided MIs	2.95	3.01	3.07	3.19	3.31
benefits	$193,410	$197,728	$201,682	$209,074	$217,096

AVOIDED STROKES

PARAMETERS

avoided cost per stroke	$49,000
smoking	8.12

	1988	1989	1990	1991	1992
start blood lead	8.25	8.23	8.22	8.20	8.19
end blood lead	6.92	6.90	6.89	6.87	6.86
start blood pressure	125.66	125.63	125.63	125.61	125.60
end blood pressure	124.16	124.13	124.12	124.10	124.09
start prob stroke	0.00347	0.00347	0.00347	0.00347	0.00347
end prob stroke	0.00338	0.00338	0.00338	0.00338	0.00337
Dif prob stroke	0.00009	0.00009	0.00009	0.00009	0.00009
population	36100	36800	37500	38800	40250
avoided strokes	1.75	1.79	1.82	1.89	1.96
benefits	$114,642	$117,194	$119,534	$123,910	$128,661

1988, increasing to 3.3 in 1992. In monetary terms, we valued an MI at $65,600, yielding total annual benefits avoided MIs at $193,000 in 1988, rising to $217,000 in 1992. [52]

Strokes. Strokes are a debilitating form of cardio-vascular disease that can leave parts of the central nervous system permanently damaged. In estimating the benefits achieved from avoided strokes, the analysis includes only medical costs and foregone wages

The estimation procedure uses the Framingham study risk regression equation assessing the probability of suffering a stroke based on systolic blood pressure, age, smoking behavior and serum cholesterol. [53] Using the same procedure employed for MIs, we estimated that 1.75 strokes can be avoided, rising to 1.96 in 1992; at $49,000 per stroke, this produces benefits of $115,000 in 1988 and $129,000 in 1992. [54]

Deaths. In addition to assessing risks for strokes, the Framing ham study estimated risk regression equations for deaths as a function of diastolic blood pressure, smoking, and cholesterol. The study looked at death from all causes associated with blood pressure, not only myocardial infarctions and strokes. [55]

52 Ibid., p. V-38 - V-39.

53 Ibid., p. V-31.

54 Ibid., p. V-40.

55 Ibid., p. V-31.

Again using the blood pressure calculations from above we substituted the blood pressure values into the risk regression equation to calculate the change in probability. We then applied the probability differential to the Boston population to estimate the reduction in expected deaths. This processs yields the estimate that 6.3 deaths can be avoided by reducing water lead levels through additional corrosion treatment, a figure that rises to 7 in 1992.

Monetizing the benefit of saving lives has always been controversial. We used the somewhat conservative estimate that saving a statistical life is worth a million dollars. Thus, the benefits in terms of lives saved in 1988 is $6,300,000, increasing to $7,000,000 in 1992.

Total Benefits for Adult Males

Having calculated the avoided myocardial infarctions, strokes, and deaths, I estimate the total benefit for this age/sex group of the population to be $6,600,000 in 1988 and 7,400,000 in 1992.

There are several substantive issues, though, that suggest that this benefit measure is somewhat conservative. First, we have excluded non-black men outside the 40–59 age group and as well as blacks of all age groups. Blacks were excluded because the Framingham and Pooling Project studies did not have a sufficiently large sample to develop risk assessments. With respect to the age issue, it is difficult to seperate the effects

of age and blood pressure outside this age group. It is likely, however, that exposure to, lead will increase the incidence of CVD in these other population groups.

Secondly, the analysis excludes other kinds of health effects of lead exposure such as renal damage. These effects have not been included because medical and epidemiological research has yet to determine precisely the relationship between blood lead and extent of physiological damage. While renal problems can often be treated, medical care is very expensive and often accompanied by adverse emotional impacts. In addition, renal damage affects all age and sex groups. It is therefore a very important omission from the benefits calculation.

Thirdly, the cardiovascular monetized estimate fails to consider quality of life issues. The benefits of avoided myocardial infarctions and strokes included only medical costs and lost wages. They fail to account for the kind of limits placed on the lives of heart attack survivors. Stroke victims who may suffer from partial paralysis and loss of speech facilities dramatically diminish the quality of life.

On the other hand, the analytic methodology used to estimate CVD related benefits may lead to an upwardly biased measure. The first bias results from the use of national blood lead data for adult men . Because adult males in Boston probably have higher blood lead levels than their counterparts in the national sample, the mean blood lead level used here is probably low. Since the relationship between blood lead and CVD is log linear, an equivalent reduction in blood lead will have a larger impact on

CVD when using a lower mean blood lead level. Therefore, an upward bias has been introduced. Sensitivity analysis, however, indicates that this bias is relatively small.

A second bias arose from the way we calculated blood pressure changes. When using the regression equations to estimate blood pressure, we substituted the mean values for all the variables. In order for such a procedure to produce unbiased reuslts, there would have to be no correlation between the independent variables. Since correlations probably do exist, the results are biased. Without knowing the correlations, though, it is impossible to determine the direction of bias.

In the absence of good health data specifically for Boston, simplifications are necessary in order to perform the analysis. The problem of bias, however, is relatively small and overwhelmingly outweighed by both the health effects and population groups excluded from the analysis. Nevertheless, we will perform sensitivity analysis in a later section to compensate for various weaknesses and test the strength of the results.

MATERIALS BENEFITS

In addition to lower lead concentrations in drinking water and its associated health benefits, additional treatment of corrosive water will further reduce materials damage. This benefits category is important when we consider the enormous investment in capital plant associated with water supply. Aside

from the petrochemical and electric power supply industries, the water supply and wastewater treatment industry represents the largest value in capital plant. Corrosion damage is particularly acute in consumer systems where water velocity has high variability, pipes are smaller, and temperatures are higher all characteristics which increase corrosion rates. Consumer systems also experience galvanic corrosion associated with the combination of lead solder and copper pipes. Because of the large capital investment, enormous savings can be achieved from extending the life of pipes and other components such as hot water heaters and air conditioning systems.

Because corrosion damage has not been examined in Boston, this analysis relies heavily on a study of Seattle performed by Kennedy Engineers in the late 1970s. Using this study is appropriate because Seattle and Boston have very corrosive water supplies. We are also hampered by the lack of direct measures of corrosion rates for Boston. Consequently, the analysis uses lead concentrations as a proxy.

In 1978, Kennedy Engineers estimated annual corrosion costs to be $7,400,000: $7,000,000 for consumers and $400,000 for the water utility or $22.68/capita in 1985 dollars. [56] Furthermore, the National Bureau of Standards believed that corrosion control techniques used in the 1970s could reduce the costs of materials damage by 20%. Based on this judgement, the avoidable per capita cost is $4.53.

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56 Ryder, Journal of the American Water Works Association, May 1980, p.283.

To calculate the additional damage costs avoided by using the treatment discussed in this paper, it is necessary to estimate the incremental reduction in corrosion. Using the Region I lead concentration data as a proxy, I estimate that an additional 25% reduction in corrosion will be achieved.[37] Applying this incremental improvement to the savings already achieved, we can expect an additional $1.13/capita reduction in materials damage annually from the new treatment or $635,0000 for the city.

Benefits can also be derived in a second way. This method utilizes the conclusions reached by the AWWA concerning corrosion control and avoidable costs. According to the AWWA, the effectiveness of corrosion control ranges from 30% to 90%, while the corrosion costs may be reduced by 15% to 50%.[38] Using the Region I data and assuming the prescribed treatment wi1l maximize corrosion control, the effectiveness of control will increase from 75% to 90%. Assuming a linear relationship between corrosion control and reduced materials damage, this 15% improvement in control will result in a 9.75% reduction in materials damage or $2.21/capita annually (.0975 reduction). Total cost reduction in Boston would therefore be $1,242,999 averaging the two estimates we arrive at a benefit figure of $939,000 annually for reduced materials damage.

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57 Karalekas, "Control of Lead, Copper, and Iron Pipe Corrosion in Boston". p. 93. NaOH treatment reduced the mean standing grab lead concentration by .087 mg/L. Additional treatment will probably reduce the concentration by another .022 mg/L which represents an additional 25% improvement.

38 AWWA, op cit., p. 590.

RESULTS AND DISCUSSION

To complete the analysis, we aggregated the costs and benefits and compared them to derive the net benefit. We also performed some sensitivity analysis to test the strength of the results and to compensate for some of the uncertainties arising from the data and the analysis. Finally, we considered how representative these results are for the nation as a whole.

On the treatment side, based on the judgment that the MWRA will employ additional pH adjustment and will add zinc orthophosphate, the utility will incur total costs of approximately $1,600,000. Because all MWRA consumers would reap the benefits of additional treatment, it is reasonable to apportion costs to Boston based on its consumption. [59] According to the MWRA demand projections, Boston consumes 43% of the region's water. [60] Therefore, Boston's share of the treatment costs based on consumption, would be $700,000. The utilization of less expensive methods could dramatically lower this figure. For example, if additional pH adjustment alone was sufficient, the costs for Boston would be only $45,000.

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59 Suburban residents would certainly see a reduction in materials damage. On the health side, benefits would probably be smaller. Lead materials, however, are found in other member communities so that additional treatment would lower lead concentrations in these other communities.

60 Metropolitan District Commission, Water demand projections, Prepared by Wallace, Floyd, Associates Inc., January 1983, p. 16.

With respect to benefits, the analysis has examined three major categories: avoided neurological damage in children reduced CVD in adult white men aged 40-59, and reduced materials damage. When added together, these benefits for Boston are $7,900,000 in 1988 increasing to $8,700,000 in 1992 (see table IV). When the aggregate costs and benefits are compared, this analysis indicates that additional corrosion control in Boston will produce a positive net benefit of $7,200,000 in 1988, increasing to $8,000,000 in l992. In terms of benefit/cost ratios, the result are 11.5:1 increasing to 12.7:1.

Because much of the work on the relationship between CVD and lead has yet to be replicated in other analyses, we should also consider the benefits excluding that category entirely in which case benefits are $1,300,000 in 1988, a value which increases slightly over the five year period. Excluding the CVD benefits, the analysis still yields a positive annual net benefit of $600,000 in 1988.

Since our calculations involve a number of stages (i.e. estimating water lead reduction, linking water lead to blood lead, etc) and uncertainities at each stage, an exhaustive sensitivity analysis could generate a huge number of possible outcomes. To simplify matters we developed only two alternate cases: the pessimistic case with highest costs and lowest benefits and the optimistic case with lowest costs and highest benefits.

For our optimistic alternative, we used the AWWA treatment cost estimate. Driven by lower chemical costs,

TABLE V

COST BENEFIT COMPARISION

	1988	1989	1990	1991	1992
net total	$7,179,176	$7,329,003	$7,466,773	$7,720,618	$7,995,324
b/c ratio	11.5	11.7	11.9	12.3	12.7
net w/o CVD	$592,511	$595,229	$598,311	$600,371	$601,878
b/c ratio w/o CVD	1.9	1.9	1.9	1.9	1.9

TABLE IV

TOTAL BENEFITS

	1988	1989	1990	1991	1992
children	$339,492	$342,210	$345,292	$347,351	$348,859
myocardial infarctions	$193,410	$197,728	$201,682	$209,074	$217,096
strokes	$114,642	$117,194	$119,534	$123,910	$128,661
deaths	$6,278,613	$6,418,852	$6,547,245	$6,787,263	$7,047,689
materials damage	$939,000	$939,000	$939,000	$939,000	$939,000
total w/o CVD	$1,278,492	$1,281,210	$1,284,292	$1,286,351	$1,287,859
total	$7,865,157	$8,014,983	$8,152,753	$8,406,599	$8,681,305

TABLE VI

TOTAL BENEFITS

	1988	1989	1990	1991	1992
children	$495,375	$499,544	$504,264	$507,002	$509,003
myocardial infarctions	$302,508	$309,279	$315,470	$327,045	$339,599
strokes	$179,239	$183,238	$186,901	$193,749	$201,181
deaths	$9,820,761	$10,040,666	$10,241,690	$10,617,533	$11,025,128
materials damage	$1,242,000	$1,242,000	$1,242,000	$1,242,000	$1,242,000
total	$12,039,883	$12,274,726	$12,490,325	$12,887,329	$13,316,911

COST BENEFIT COMPARISION

	1988	1989	1990	1991	1992
net total	$11,499,866	$11,734,709	$11,950,308	$12,347,312	$12,776,893
b/c ratio	17.6	17.9	18.2	18.8	19.4

Boston's share of annual treatment cost would be $550,000. To calculate benefits we used the following assumptions: apply water lead data to 70% of the population; use the high 95% confidence interval for water lead reduction - .026 mg/L; and the high estimate for materials damage - $1,242,000. Under these assumptions we calculated annual benefits to be $11,500,000 for Boston in 1988, rising to $12,775,000 in 1992 (see table VI).

In the pessimistic case, we based treatment cost estimates on EPA's high phosphate feed rate assumption. Boston's share of the region's annual cost would be $860,000. On the benefits side, we employed the following assumptions to develop the low estimate: apply water lead data applies to only 40% of the population; use the low 95% confidence interval for water lead reduction - .018 mg/L; and the low estimate for materials damage - $635,000. This scenario yielded $3,950,000 in annual net benefits for Boston in 1988, rising to $4,330,000 in 1992 (see table VII).

Even under pessimistic assumptions, the Boston case study clearly confirms the findings of EPA's earlier studies of the whole country: in terms of health and materials benefits, corrosion control is a worthwhile investment. What is even more impressive about these results is the fact that they represent the marginal effects. Like many pollution control activities, corrosion control is often characterized by decreasing marginal benefits. This implies that the benefit per dollar of treatment declines as additional treatment is implemented. Therefore, in Boston, a city that already controls corrosion somewhat, the

marginal benefits generated by additional treatment will be much lower than the marginal benefit for communities that do not currently treat their water. On the other hand, health benefits are more pronounced because the presence of lead in the water distribution system is more widespread in Boston than in many other communities.

The discussion of marginal benefits, though does raise one problem not adequately addressed in this paper. While this analysis has examined the combined benefits of additional and better controlled pH adjustment and zinc orthophosphate, it was not possible to isolate the incremental benefits produced by each treatment alone. We are therefore left with the small possibility that the vast proportion of lead reduction results from the relatively inexpensive pH adjustment, while very little results from the relatively expensive orthophosphate treatment. Consequently, we can conceive of instances where large additional investments in treatment are required to meet the contemplated MCL but are not warranted in terms of the health and materials benefits they yield. In such instances, EPA should consider granting a waiver. Otherwise, inflexible enforcement of the MCL may force water utilities to invest additional resources to treat corrosion related contamination when such resources could be directed at other problems to yield greater water quality benefits.

TABLE VII

TOTAL BENEFITS

	1988	1989	1990	1991	1992
children	$180,096	$181,639	$183,401	$184,343	$185,021
myocardial infarctions	$114,594	$117,146	$119,487	$123,862	$128,612
Strokes	$67,951	$69,459	$70,846	$73,436	$76,251
deaths	$3,719,837	$3,802,728	$3,878,725	$4,020,778	$4,174,982
materials damage	$635,000	$635,000	$635,000	$635,000	$635,000
total	$4,717,477	$4,805,973	$4,887,459	$5,037,419	$5,199,866

COST BENEFIT COMPARISION

	1988	1989	1990	1991	1992
net total	$3,848,092	$3,936,587	$4,018,073	$4,168,034	$4,330,480
b/c ratio	6.9	7.0	7.1	7.3	7.6

RECOMMENDATIONS

My analysis shows that EPA should lower the MCL for lead from .05 mg/l to .01 mg/l. The measures necessary to accomplish this task are relatively inexpensive and the technologies are simple. The potential benefits are large and extend beyond the health effects of lead exposure. Corrosion control will lower the level of other toxic and nuisance contaminants and reduce materials damage.

Along with the change in the MCL, EPA should consider instituting a waiver system. While all communities that have corrosion related lead contamination of their drinking water should undertake corrosion control to reduce lead concentrations, EPA should be sensitive to mariginal costs and benefits, and adopt a secondary standard of perhaps .015 mg/L. If a community achieves this standard and can demonstrate that additional improvements would not be warranted in terms of treatment costs, a waiver from the .01 mg/L standard might be indicated. The latter requirement will be increasingly difficult to meet, though, as additional health effects of lead are better understood and monetized (i.e. renal damage) Consequently, waivers would only be granted in cases where a community just barely exceeds the MCL and further reductions in lead would require significant new investments in corrosion control.

Finally, EPA, through its regional offices, should provide technical assistance to cities and municipalities. Before a community chooses an appropriate treatment method it must first